UNIVERSITI TEKNOLOGI MARA

MICROWAVE NON-DESTRUCTIVE TESTING OF SEMICONDUCTOR MATERIALS

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SYMBOLS

V	Voltage
I	Current
C	Capacitance
Q	Charge
A	area of the plates of the capacitor
P	Polarization
$\overline{D}$	electric flux density (Coulombs/meter^2)
$\overline{E}$	electric field intensity (Volt/meter)
$\overline{H}$	magnetic field intensity (Ampere/meter)
$\overline{J}$	current density (Ampere/meter^2)
$\overline{B}$	magnetic flux density (Webers/meter^2)
$\overline{M}$	magnetic current density (Volt/meter^2)
ρ	electric charge density (Coulombs/meter^3)
f	Frequency
χ_e	electric susceptibility
ε_0	permittivity of free space ($= 8.854 \times 10^{-12}$ Farad/meter)
μ_0	permeability of free space ($= 4\pi \times 10^{-7}$ Henry/meter)
ε	Permittivity
ε^*	complex permittivity
$\varepsilon^{'}$	real part of complex permittivity
$\varepsilon^{''}$	imaginary part of complex permittivity (loss factor)
μ	Permeability
μ^*	complex permeability
u	velocity of wave
$\varepsilon_c^{''}$	dielectric losses due to ionic conductivity
$\varepsilon_d^{''}$	dielectric losses due to dipolar polarization
$\varepsilon_e^{''}$	dielectric losses due to electronic polarization
$\varepsilon_a^{''}$	dielectric losses due to atomic (ionic) polarization
$\varepsilon_i^{''}$	dielectric losses due to interfacial polarization
∇	del operator
$\dfrac{\partial}{\partial t}$	partial derivative with respect to time
j	$\sqrt{-1}$

π	pi (= 3.14)
c	speed of light (= 2.998x10^8 meter/sec)
σ	Conductivity
τ	relaxation time
e	electronic charge (= 1.60x10^{-19} Coulombs)
n	Electron
p	Hole
μ_e	mobility of electron
μ_h	mobility of hole
E_{loc}	local electric field
E	electric field
N	molecules per unit atom
α_T	molecular polarizability
g	ratio between local electric field and electric field
n_i	intrinsic carrier concentration
R_s	sheet resistance
λ_0	wavelength in free-space
λ_m	wavelength in the material
α	attenuation constant
β	phase constant
ω	angular frequency
γ	propagation constant
δ	skin depth
d	sample thickness
l	distance between parallel-plate capacitor
α_e	electronic polarization
α_i	ionic polarization
S_{11}	forward reflection coefficient
S_{21}	forward transmission coefficient
S_{11}^m	measured forward reflection coefficient
S_{11}^c	calculated forward reflection coefficient
S_{21}^m	measured forward transmission coefficient
S_{21}^c	calculated forward transmission coefficient
θ_{11}	forward reflection coefficient phase

θ_{21}	forward transmission coefficient phase
TE_{10}	transverse electric mode
Z_L	load impedance
Z_{in}	input impedance
Z_0	characteristic impedance
Γ	reflection coefficient
Γ_L	reflection coefficient at the load
T	transmission coefficient
a_1	forward incident wave
a_2	reverse incident wave
b_1	forward scattered wave
b_2	reverse scattered wave
E_{DF}	forward directivity error
E_{SF}	forward source match error
E_{XF}	forward isolation error
E_{TF}	forward transmission tracking error
E_{RF}	forward reflection tracking error
E_{LF}	forward load match error
E_{DR}	reverse directivity error
E_{SR}	reverse source match error
E_{XR}	reverse isolation error
E_{TR}	reverse transmission tracking error
E_{RR}	reverse reflection tracking error
E_{LR}	reverse load match error

ABBREVIATIONS

AC	alternating current
DC	direct current
CW	continuous wave
FM	frequency-modulated
EM	Electromagnetic
PVC	Polyvinyl-chloride
VNA	vector network analyzer
NDT	non-destructive testing
DUT	device under test
LRL	line-reflect-line
TRL	thru-reflect-line
MHz	Megahertz
GHz	Gigahertz
RF	radio frequency
IC	intergrated circuit
MNDT	microwave non-destructive testing
RDWG	rectangular dielectric waveguide
m	Meter
ns	Nanosecond
in	Inch
sec	Second
mm	Millimeter

ABSTRACT

A contactless and non-destructive microwave method has been developed to characterize silicon semiconductor wafers from reflection and transmission measurements made in free space at normal incidence. The measurement system consists of a pair of spot-focusing horn lens antenna, mode transitions, coaxial cables and a vector network analyzer (VNA). Two methods were developed namely the transmission and the reflection methods. From the complex permittivity, the resistivity and conductivity of Si wafers can be obtained. Results for p-type and n-type doped silicon wafers are reported in the frequency range of 8.5 to 12.5 GHz. The measurements were conducted in the frequency domain.

The research found that, the dielectric constant of the silicon wafers are relatively constant, varying slightly over the frequency range. As the frequency increased, the loss factor of the wafers decreased. The dielectric losses were the ionic and electronic losses due to dipoles orientation. The loss factor, loss tangent and conductivity of the doped wafers are higher than the undoped type. The conductivity of silicon wafers increases with frequency. Despite lower doping concentration, the n-type wafers showed the highest conductivity due to the higher mobility of electrons compared to holes. There is no significant difference between the AC and DC resistivity of the silicon wafers. This could be due to the non-polar property of the wafers. The skin depth of the silicon wafers decrease with increasing conductivity. This technique will be a major contribution to the semiconductor industry since it is accurate, quick, broadband, contactless and non-destructive. This is highly desirable since the silicon wafer is brittle, fragile and requires high purity level.

CHAPTER ONE

INTRODUCTION

1.1 Introduction

Microwave frequencies occupy a part of the electromagnetic spectrum extending from 300 MHz to 300 GHz [1]. Applications of microwaves in various areas have been extensive and varied particularly in telecommunications and radar. The most popular application of microwave power is in microwave ovens for domestic and commercial cooking. Industrial applications of microwave power include applications in industries such as food, rubber, chemicals, plastics, textiles, building materials, oil, coal and pharmaceuticals. Others include continuous moisture-content monitoring, monitoring of geometrical dimensions and determination of solid and liquid levels.

The ability of microwaves to penetrate most dielectric materials, and their relatively short wavelengths make them suitable for non-destructive measurements (a contactless, free-space technique). Since the penetration of microwaves in good conducting materials is very small, microwave non-destructive testing (MNDT) techniques are mainly used for non-metallic materials. The spatial resolution of these techniques depends on the wavelength of the wave. For the commonly used microwave band of 3 to 100 GHz, the wavelength varies from 100 mm to 3 mm. Major studies of the dielectric properties were done in the microwave range since this method is non-invasive and non-destructive - practically no sample preparation is required. These techniques have advantages over other non-destructive methods (such as radiography, ultrasonics and eddy current) by way of low cost, good penetration in non-metallic materials, good resolution and contactless feature of the microwave sensor.

Complex permittivity and permeability are determined by the material's molecular structure, so they can be related to other properties of interest as well. Measuring them can provide critical insight to applications in many industries. It can be useful in all stages of a product's lifecycle: design, incoming inspection, process monitoring, and quality assurance. For example, it can provide important information about materials used in state-of-the-art radio frequency (RF) and microwave electronic components. Even biomass, bulk density, bacterial content, and chemical concentration can be related to a material's electromagnetic properties.

The choice of substrate material is important for high frequency integrated circuit design. The substrate must be a semiconductor material to accommodate the fabrication of active devices. Besides substrate thickness and strip width, substrate permittivity is another important parameter for high frequency IC design. Characteristics such as complex permittivity (dielectric constant, loss tangent and loss factor) and resistivity must be evaluated because the design of these circuits rely critically on these parameters. The dielectric properties of materials dictate to a large extent the response of the devices when subjected to RF or microwave fields. In addition to polarization effects, at microwave frequencies, these properties may change significantly due to radiation loss or other spurious effects such as electromagnetic coupling, thus posing problem to the IC designers. Therefore, knowledge of these properties will contribute significant understanding and ultimately will assist high frequency IC designers.

For this reason, silicon semiconductor wafer is chosen as the sample in this study. Silicon is one of the most common substrate for high frequency ICs. The wider bandgap of silicon results in electronic devices that are capable of operating up to around 200 °C. Silicon, in contrast to germanium, readily accommodates itself a stable passivation layer on the surface by forming silicon dioxide (SiO_2), which provides a high degree of protection to the underlying devices [2]. In addition, silicon wafer can be considered a perfect planar sample due to its single-crystal property, which have a high degree of regular geometric periodicity throughout the entire volume of material and are capable of being cleaved at precise planes [3]. Thus is suitable for this technique which allows reflection and transmission measurements for normal incidence.

To date, various versions of microwave measurement techniques have been reported for the characterization of semiconductors but none have used free-space method, which is contactless and non-destructive [4-8]. This research presents a free-space method for measurement of complex permittivity of semiconductor materials at microwave frequencies using reflection and transmission techniques. It thus yields values of microwave permittivity and microwave conductivity simultaneously. Since contacts are not used, the methods have advantages over other conventional conductivity measurements method. The system consists of a pair of spot-focusing horn lens antenna, mode transitions, coaxial cables and a vector network analyzer (VNA).

The inaccuracies in free-space measurements are due to two main sources of errors; diffraction effects at the edges of the specimen and multiple reflection between horn lens antennas and the sample. The spot-focusing antennas are used for minimizing diffraction effects while free-space TRL (thru, reflect, line) calibration method implemented on VNA along with time domain gating feature of the VNA reduces errors due to multiple reflections.

1.2 Problem Statement

An important consideration in the construction of semiconductor devices is the control and measurement of the electrical properties of the material. The semiconductor transport properties such as permittivity, resistivity, conductivity and mobility must be evaluated since at microwave frequencies these properties may change significantly due to dielectric loss or other undesired spurious effects such as electromagnetic coupling thus posing problems for high frequency IC designers. At microwave frequencies, the dielectric loss is associated with formation of electric dipoles due to electronic and ionic polarizations. These dielectric losses have contributions to the permittivity and conductivity of semiconductor materials.

Much information about the fundamental processes whereby electrons in semiconductors are scattered (i.e. make spontaneous transitions from one quantum state to another) is contained in transport properties such as conductivity and mobility. Currently, the measurement of these properties with direct current has been very useful in the study of different mechanisms, which cause transitions between the various stationary states. The ac transport properties, which are obtained by microwave measurement differ from the dc properties by having real and imaginary parts. This added information reflects many details relevant to the scattering processes, thus can be an extremely useful means of studying the detail scattering mechanisms. Knowlegde of scattering effects is also important to high frequency IC designer since the conduction mechanism affects circuit losses and contribute to noise. This is the primary advantage of characterizing semiconductors with microwaves rather than with dc.

In contrast to NDT, other methods performed using ohmic contacts introduce contact noise. This results in low signal to noise ratio, which hampers the measurement. Furthermore, the use of contacts destroys the sample. Currently, the DC four-point probe method [9] is widely used for the measurement of resistivity in semiconductor material where the probes are in direct contact with the wafer thus inducing probe damage and adding contamination. This occur even at high temperature where contacting probes could react with the semiconductor. Furthermore four-point probe method reveals dc properties only and are thus not much use for high frequency IC design. At high frequencies other physical effects such as surface wave modes add complexity and will give rise to further measurement errors.

Until today, various researches have been carried out to develop characterization tools to evaluate semiconductor materials. Waveguide methods are widely used, where the sample is precisely cut to fit inside a waveguide. In comparing rectangular and circular waveguides, rectangular samples are easier to make than circular ones, but they can only be used over a limited frequency range. Circular waveguide can extend over wide frequency bands but sample preparation is difficult. Errors associated with the waveguide methods are caused by incomplete filling of the waveguide by the sample. In addition sample preparation is destructive and time consuming. Another microwave method is the cavity resonator. This method gives the conductivity and permittivity from measurements of changes in quality factor and frequency, which result when a sample is inserted into the cavity. Cavity methods are very accurate and can measure loss tangent of very low loss material accurately but it employs only single frequency per cavity.

For complete characterization of materials, a large number of measurements over a wide frequency band are required. This process is obviously time-consuming. Therefore the development of a technique capable of covering a broad frequency range with acceptable accuracy is highly desirable. Free-space microwave probing methods overcome many of these problems. These methods make possible a very accurate, quick, broadband, contactless and non-destructive measurement of materials. They allow sample to be of any shape provided its size is greater than three times the beamwidth of the antenna at the focus. The methods are useful above all for the measurement of plate materials such as semiconductor wafers. Furthermore, measurements by this free-space method can be made without inducing probe damage and adding contamination. These conditions have led to development of a new method of measurement which is fully contactless and non-destructive and can be carried out at low or high temperatures, and in strong magnetic and electric fields.

1.3 Objectives

The main objective of this research is to develop a non-destructive testing technique to measure the complex permittivity of silicon wafers at microwave frequencies. A computer modeling to calculate the reflection and transmission coefficients and to correlate the dielectric properties of the wafers with the electrical properties is developed.

1.4 Scope of Research

In this work, the magnitude and phase of the reflection and transmission signals were measured. Two free-space methods were developed, namely, reflection and transmission methods.

The reflection method is also known as the short circuit method. In this method, the complex forward reflection coefficient is measured by inserting a perfectly conducting plate behind the silicon wafers at the focus of the lens antenna. By implementing an algorithm which finds the zeros of the error function, the complex permittivities are then calculated from the reflection coefficients.

The transmission method employs a pair of quarter-wavelength impedance transformer to reduce the reflectivity of the sample. By this method, the complex permittivity of semiconductor materials is calculated from the complex transmission coefficient by substituting the values of the impedance transformer. An algorithm was developed which calculates complex permittivities from measured magnitude and phase of the transmission coefficients. This algorithm involves calculation of the actual transmission coefficient due to the impedance transformer and calculation of new complex permittivity guess by using zero finding technique. From the complex permittivity, the resistivity and conductivity can be obtained.