Measurement of Dielectric Constant of Silicon Wafer using Microwave Non-Destructive Testing and Direct Current Technique

Nadia binti Md Kamal
Bachelor of Electrical Engineering (Hons.)
Faculty of Electrical Engineering
Universiti Teknologi Mara
40450 Shah Alam, Selangor, Malaysia
Email: nadiamdkamal@gmail.com

Abstract- **This paper presents comparison between measurement of dielectric constant of silicon wafer by using MNDT which is at high frequency and by using HIOKI 3532-50 LCR HiTESTER which at low frequency. Measurement of dielectric properties of silicon wafer at microwave frequencies is performed in free space using a pair of spot-focusing horn lens antennas, mode transitions, coaxial cable and vector network analyser (VNA). A contactless and non-destructive microwave method has been developed to characterize silicon semiconductor wafer from reflection and transmission measurement made in free space at normal incident. In this method, the free-space reflection and transmission coefficients, S_{11} and S_{21} are measured for silicon wafer sandwiched between two teflon plates which are quarter-wavelength at mid-band. The actual reflection and transmission coefficient, S_{11} and S_{21} of the silicon wafers are calculated from the measured S_{11} and S_{21} of the teflon plate-silicon wafer-teflon plate assembly in which the complex permittivity and thickness of the teflon plates are known. Result for p-type and n-type doped silicon wafer are reported in frequency range of 10GHz to 12GHz. As a comparison, a measurement at low frequency using DC method has been conducted. The frequency range is reported from 0.1 kHz to 50 kHz.**

Keyword- **Microwave Non-Destructive Testing (MNDT), Direct Current (DC).**

I. INTRODUCTION

In the construction of semiconductor devices, the control and measurement of the electrical properties of the material is very crucial. Permittivity and thickness must be evaluated since at microwave frequencies these properties may change significantly due to dielectric loss. The SiO_2 dielectric layer has been used for many decades due its physical and chemical properties. In addition, SiO_2 is also an excellent insulator because of its large 8-9 eV energy bandgap. The large barrier height of 3.1 eV and 4.5 eV for hole and electrons, respectively, keeps carriers in the channel. The dielectric properties are important for design of integrated circuits.

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. Knowledge of scattering effects is also important to high frequency IC designer since the conduction mechanism affects circuit losses and contributes to noise. This is the primary advantage of characterizing semiconductors with microwaves rather than with dc. Compared with other methods using ohmic contacts introduce noise. Another method is the cavity resonator which gives the conductivity and permittivity from measurement of changes in quality factor and frequency. Cavity method is very accurate but it only gives single frequency per cavity. By using waveguide methods, the sample must cut to fit inside waveguide thus sample preparation is destructive and time consuming [1]. The DC four-point probe method [2] is widely used for the measurement of resistivity in semiconductor material. The probes are directly contact with the wafer thus inducing probe damage and adding contaminant.

For high frequency experiment, a high-frequency millimeter wave must be used in order to ensure the transmit millimeter wave attenuate rapidly inside the semiconductor, so that the reflection from the bottom surface of the wafer can be neglect. Thereby, it becomes possible to consider the reflection only on the top surface of the semiconductor, thus, the millimeter wave response signal is not affected by the thickness of the gate dielectric. Microwave non-destructive testing (MNDT) of materials is an important science which involve development of sensors/probes, methods and calibration techniques for detection of flaws, cracks, defects, voids, inhomogenities, moisture content (MC), etc. by means of microwaves [3]. They are increasing being used for quality control and condition assessment of concrete structures. In this experiment, we describe a contactless method for measuring complex permittivity of semiconductor materials by a microwave non-destructive technique.

This paper presents a free-space method for measurement of complex permittivity of semiconductor materials at microwave frequency using reflection and transmission technique. MNDT techniques using free-space method have advantages over other conventional conductivity measurements method. The free-space reflection and transmission coefficients, S_{11} and S_{21} for normal incident plane wave are measured for silicon wafer sandwiched between two Teflon plates which are quarter wavelength at mid-band [4]. The actual reflection and transmission coefficient, S_{11} and S_{21} of the silicon wafers are calculated from the measured S_{11} and S_{21} of the Teflon plate-silicon wafer-Teflon plate assembly in which the complex permittivity and thickness of the Teflon plates are known. Teflon is used because of the thin samples and the accuracy of measurement of S_{11} and S_{21} is poor because of sagging of the sample when mounted on the sample holder. The complex permittivity were calculated as a function of frequency and plotted in dielectric constant [5]. The parameters exhibit some frequency dependence. Results are reported in the frequency range of 10GHz until 12GHz.

At low frequency experiment, we use HIOKI 3532-50 LCR HiTESTER for measuring the real and imaginary impedance parameters. It can measure higher frequency range from 42 Hz to 5 MHz. This equipment has high speed measurement of 5ms. This means that line tact times can be further shortened, by increased line efficiency. It also has high precision measurement of ±0.08% basic accuracy [6]. The measurement method source was by using constant current or constant voltage. The silicon sample must be cut by using diamond cutter because the stage holder is very small. The frequencies used for measurement are 0.1 kHz to 50 kHz.

II. THEORY

A. *Free space Microwave Measurement*

The free-space reflection and transmission coefficients, S_{11}, and S_{21} for a normally incident plane wave are measured for silicon wafer. In this experiment, a quarter-wavelength impedance transformer of Teflon™ is used as an impedance matching. From Figure 1, to determine the complex permittivity by transmission method, the silicon wafer is sandwiched between two Teflon™ plates which are quarter-wavelength at midband. Teflon™-silicon- Teflon™ give the result of S_{11a} and S_{21a} . Then the real value of S_{11} and S_{21} of the silicon wafer can be calculated. The flowchart of the calculation program is shown in Figure 2.

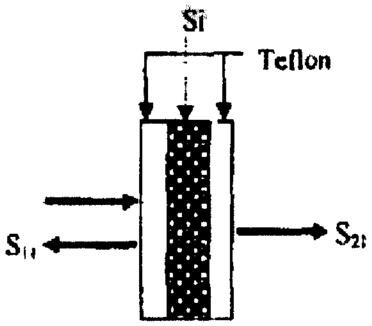

Figure 1: Schematic diagram of Teflon – silicon – Teflon assembly

To calculate the complex permittivity, a Fortran program had been developed as in [1]. Reference [4] shows the formula to calculate the complex permittivity of the silicon wafer by using transmission method.

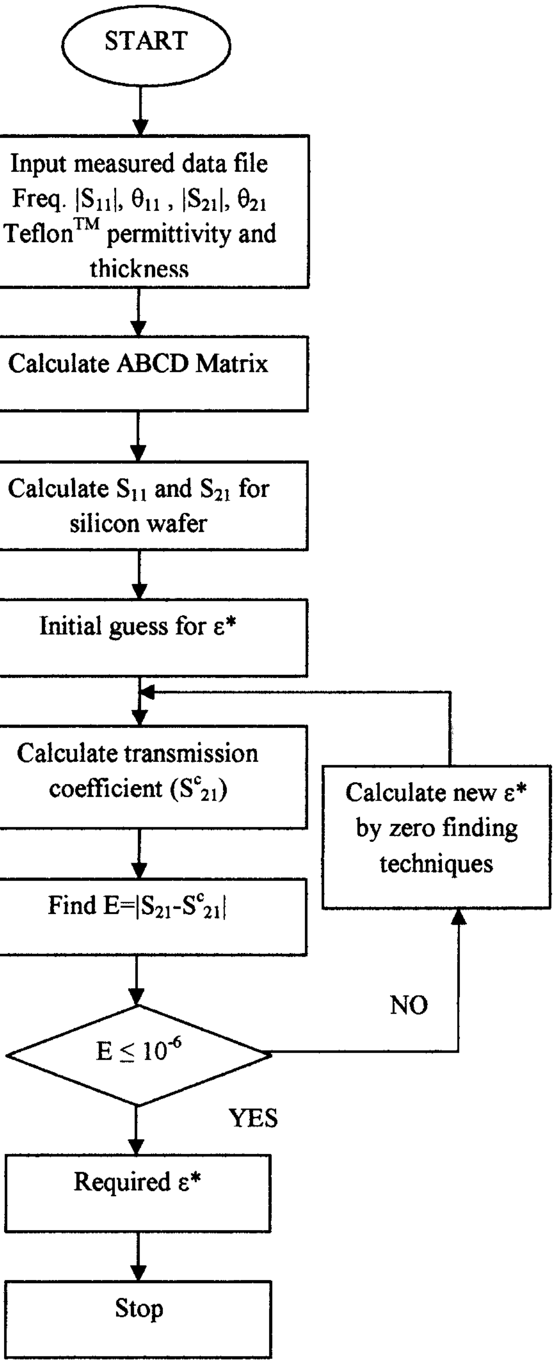

Figure 2: Flow chart for calculating dielectric constant for silicon wafer

B. *Direct Current technique*

HIOKI 3532-50 LCR HiTESTER, gives the result of frequency,f real impedance, Z_r and imaginary impedance,Z_i. The calculations for dielectric constant of silicon wafer, ε' is:

$$\varepsilon' = \frac{Z_i}{(Z_r{}^2 + Z_i{}^2)(2\pi f)(C_o)}$$

f = frequency
C_o = Capacitance at free space

$$C_o = \frac{\varepsilon_0 A}{d}$$

ε_o = free space permittivity, 8.85 x 10^{-12} F/m
A = area of the circle of stage holder
d = dielectric thickness

III. MEASUREMENT SYSTEM

A. *Measurement by using MNDT*

The measurement system consists of WILTRON 37269B Vector Network Analyzer (VNA) which is connected to pair of spot focusing antenna by using circular to rectangular waveguide analyzer. These antennas have two-equal plano-convex lenses mounted back to back in a conical horn antenna. One plano-convex lens gives an electromagnetic plane wave and the other plano-convex lens focuses the electromagnetic radiation at the focus. For these antennas, the ratio of focal distance to antenna diameter (F/D) of the lens is equal to one and D is approximately 30.5 cm. The distance between these antennas can be change with an accuracy of 25.4 μm by using dial indicator. A sample holder is placed at the common focal plane for holding silicon wafer and is mounted on a micrometer-driven carriage. This network analyzer is used to make accurate reflection and transmission (S-parameters) measurements in free-space using line-reflect-line calibration model. Because of multiple reflections between coaxial-to-rectangular waveguide adapters, rectangular-to-circular waveguide transitions and horn lens antennas, there is a need to calibrate the measurement system in free-space for S-parameter measurements. We have implemented free-space LRL calibration technique [7, 8]. This calibration technique along with smoothing or time domain gating feature of the network analyzer can eliminate effects of multiple reflections. It is known that LRL calibration technique can produce the highest quality calibration available. Also, it is easier to realize LRL calibration standards in free-space as compared with open, short and matched termination standards used in coaxial and waveguide media. So, LRL calibration is the best calibration technique for the free-space medium. Free-space LRL calibration is implemented in free-space by establishing three standards.

The reference planes for port 1 and port 2 are located at the focal planes of transmit and receive antennas. The through standard is realized by keeping the distance between two antennas equal to twice the focal distance. It means that there is a common focal plane for the through standard. The line standard is achieved by separating the focal planes of the two antennas. The distance between focal planes is approximately a quarter wavelength at mid-band. The reflect standards for port 1 (transmit horn) and port 2 (receive horn) are obtained by placing a metal plate 3.18mm of thickness on sample holder at the reference plane. It is shown as in the Figure 3. The standard is achieved by separating the focal planes of the two antennas by a distance equal to a quarter wavelength at mid-band. For this measurement we set the quarter wavelength at 7.5mm since we used the frequency from 8GHz to 12GHz.

Figure 3: Calibration of S_{11} parameter

For S_{21} calibration, we move the metal plate and set at micrometer 0.00mm. VNA must be calibrating to reducing error. During calibration, magnitude and phase of S_{11} are within ±0.2 dB and ±1° of theoretical value of 0 dB and 180° for the metal plate. While the measured magnitude and phase of S_{21} are within ± 0.05 dB and ± 0.2° of the theoretical values of 0 dB and 0°. The actual values of S_{11} and S_{21} of sample are calculated from the measured S_{11} and S_{21} of Teflon-silicon-Teflon plate from the knowledge of the complex permittivity and thickness of the Teflon plates. Teflon real permittivity is 2.1. The results obtained at mid-band frequency were 2.13 this value is in good agreement with published result.


Figure 4: Measurement in progress

B. Measurement by using HIOKI 3532-50 LCR HiTESTER

The equipment consists of the monitor, stage holder, and the HIOKI 3532-50 LCR HiTESTER. The LCR had simple touch panel operation. Before the measurement the equipment must be calibrated. The stage holder is connected with LCR by alligator clips.

Open and short circuit calibration has to be done first. For open calibration, the stage holder must be pull up and make sure there are some distance as shown in Figure 5. After that press the button run to calibrate. For short circuit calibration, before pressing the short button at the LCR, we must make sure the stage holder is closed with each other. It is shown in Figure 6. Then press the button all and button run. Then put the silicon wafer at the stage holder and close it as shown in Figure 8. Measurement data captured by a personal computer can be displayed graphically by using standard spreadsheet software. The results are captured into Excel. In the computer, select the frequency characteristic. The values of frequency for this experiment are 0.1 kHz until 50 kHz and the data count are 1000, then measurement is done. Take the diameter of the stage holder which is 2.4 cm to calculate the area of the circle. Figure 5 to Figure 8 shows the step of procedure while conducting the measurement of silicon wafer sample by using dc technique.


Figure 5: Pull up the stage holder


Figure 6: The stage holder close

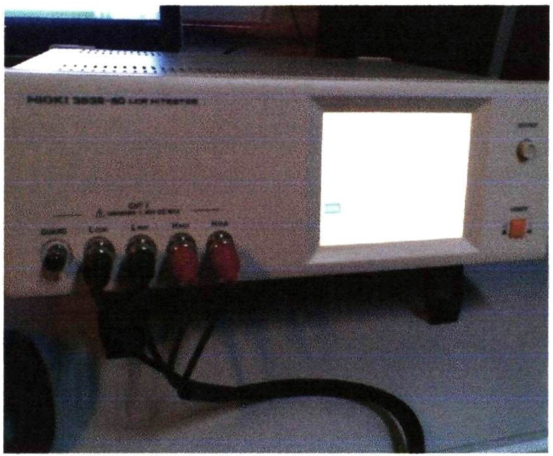

Figure 7: HIOKI 3532-50 LCR HiTESTER


Figure 8: Measurement in progress

IV. RESULT AND DISCUSSION

A. *Result by using free space method*

The permittivity of semiconductor is extracted from S_{11} and S_{21} parameters. At X band which is 8GHz until 12GHz, take the S_{11} and S_{21} value before using Fortran programming. But only value from 10GHz until 12GHz is plotted because the sample is small. The data specification of silicon wafer as shown in Table 1.

Table 1: Specification for silicon wafers

Sample	1	2
Type/Dopant	P-type	N-type
Diameter (mm)	100	100
Thickness (μm)	525 ± 25	525 ± 25
Resistivity (Ω)	1-10	1-10
Surface	Single side polished	Single side polished

The result shown in Figure 9 and Figure 10 are the measured value of dielectric constant for both p-type and n-type silicon wafers are from 11.30 to 12.32 and 11.01 to 12.47 respectively. The values of dielectric constant are shown in Table 2 and Table 3. As a comparison a reported by Roy et al [9] give values between 11.01 to 12.00 for p-type samples, while Holms et al. [10] quoted figures of 12.41 and 12.27 ±0.05 for n-type and p-type respectively. Reference [5] also shows that the measured values of dielectric constant for n-type and p-type are 10.00 to 12.75 and 10.00 to 12.50. The wide range values obtained for the range of dielectric constant occur because of the error in the measured value of the magnitude of the reflection coefficient S_{11}, transmission coefficient and their phase angle. The different values are due to the air-gap effect of the sample assembly. The presence of free-carriers from the doping material which modify the characteristic of the wafer, thus causing variation in dielectric constant of the wafers. The error also can happen due to the interruption of the measurement system after the calibration.

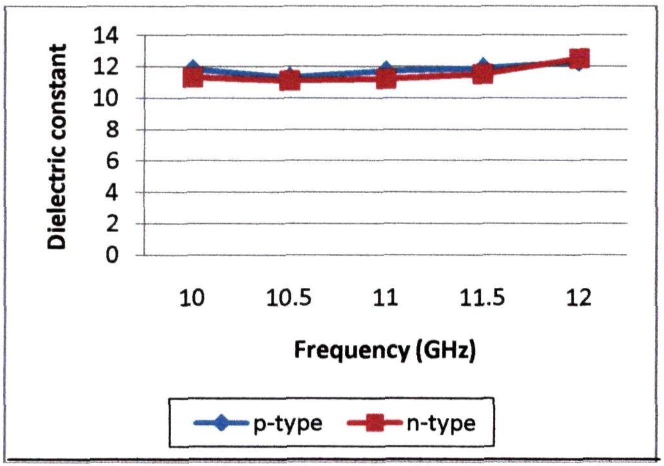

Figure 9: bare silicon wafer (shiny side)

Table 2: Dielectric constant for bare silicon wafer (shiny side) by using MNDT

Frequency (GHz)	Sample	
	N-type	P-type
10.0	11.323	11.769
10.5	11.181	11.347
11.0	11.232	11.662
11.5	11.521	11.987
12.0	12.473	12.320

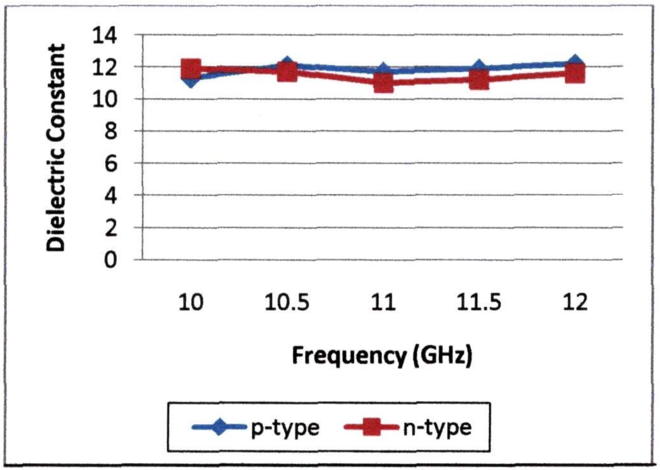

Figure 10: bare silicon wafer (dull side)

Table 3: Dielectric constant for bare silicon wafer (dull side) by using MNDT

Frequency (GHz)	Sample	
	N-type	P-type
10.0	11.897	11.302
10.5	11.685	12.050
11.0	11.013	11.750
11.5	11.232	11.862
12.0	11.678	12.232

B. *Result by using dc technique*

Result by using dc technique low frequency, are shown in Figure 11. The measurement only had one side. The results of dielectric constant that we calculate from the Excel for p-type were in the range of 11.2 until 12.3 and for n-type were between 10 until 12. The values of dielectric constant by using dc technique are in Table 3. The slightly lower values obtained in this method maybe due to the probe that are direct contact to the wafer which can cause probe damage and adding contaminant. This occurs when there are high temperature where contacting probes could react with the semiconductor. The silicon that we cut using diamond cutter were not fulfill the stage holder. Thus, the area of the wafer was not really accurate.

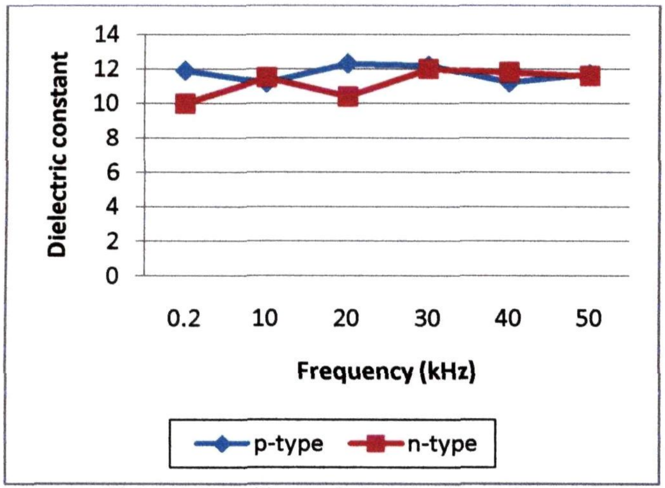

Figure 11: Pure silicon wafer by using dc technique

Table 3: Dielectric constant of bare silicon wafer using dc technique

Frequency (kHz)	Sample	
	N-type	P-type
0.2	10.0	11.9
10	11.5	11.2
20	10.4	12.3
30	12.0	12.2
40	11.8	11.2
50	11.6	11.7

V. CONCLUSION

MNDT can be used to measure values of complex permittivity of silicon wafer in the microwave frequency range. The free space method is contactless and thus introduces no damage to sample, but it requires complex instrument and techniques that must be used. In the future, more types of semiconductor wafer can be characterized and measured. The electrical properties of semiconductor device are undamaged. Since MNDT is a nondestructive technique.

The dc techniques use simple instrument and calculation. But the probes were contact with the sample and the wafer must be cut into small size. The result for both technique shows similarity thus proves that both techniques can be used to measure the dielectric constant.

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