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Free Space Microwave Characterization of Silicon Wafers for Microelectronic Applications

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ABSTRACT

A contactless and non-destructive microwave method has been developed to characterize silicon semiconductor wafers from reflection and transmission measurements made at normal incidence using MNDT. The measurement system consists of a pair of spot-focusing horn lens antenna, mode transitions, coaxial cables and a vector network analyzer (VNA). In this method, the free-space reflection and transmission coefficients, S_{11} *and* S_{21} *are measured for silicon wafers sandwiched between two Teflon plates of 5mm thickness which act as a quarter-wave transformer at mid-band. The actual reflection and transmission coefficients,* S_{11} *and* S_{21} *of the silicon wafers are then calculated from the measured* S_{11} *and* S_{21} *using ABCD matrix transformation in which the complex permittivity and thickness of the Teflon plates are known. From the complex permittivity, the resistivity and conductivity can be obtained. Results for p-type and n-type doped silicon wafers are reported in the frequency range of 11 – 12.5 GHz. The dielectric constant of silicon wafer obtained by this method agrees well with that measured in the same frequency range by other conventional methods.*

Introduction

The ability of electromagnetic waves to penetrate most dielectric materials, and their relatively short wavelengths at radio, microwave and millimeter

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wave frequencies, make them suitable for non-destructive measurements. The term microwaves refer to alternating current signals with frequencies between 300 MHz (3×10^8 Hz) and 300 GHz (3×10^{11} Hz). Since the penetration of microwaves in good conducting materials is very small, microwave non-destructive testing (MNDT) technique is mainly used for non-metallic materials. In MNDT technique, the measured parameters are reflection coefficient, transmission coefficient, dielectric constant, loss factor and loss tangent as a function of frequency. The spatial resolution of this technique depends on the wavelength of the wave.

The choice of substrate material is important for the high frequency integrated circuits 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. At microwave frequencies these properties may change significantly due to dielectric loss or other spurious effects such as electromagnetic coupling, thus posing problem to the IC designers. Knowledge of these properties will therefore contribute significant understanding and ultimately will assist high frequency IC designers.

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 as well as to the energy band structure, thus can be an extremely useful means of studying the detail scattering mechanisms. 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 [1] 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 the 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.

Free-space microwave probing methods overcome many of these problems. These conditions have led us to develop a method of measurement which is fully contactless and non-destructive and can be carried out at high or low temperatures, in strong magnetic and electric fields. Until today, various researches have been carried out to develop characterization tools to evaluate semiconductor materials at microwave frequencies [2-7] but none have used spot focusing antennas.

The objectives of this project can be summarized as follows:

a. To measure dielectric properties of semiconductor wafers using microwave non-destructive technique.
b. To establish a correlation between the dielectric properties of semiconductor wafers evaluated from microwave non-destructive technique with the electrical properties.
c. To develop computer programs for the calculation of complex permittivity.
d. To develop a theoretical modeling using computers to enable computation of reflection and transmission coefficients.

In this report, we include results of complex permittivity for p-type and n-type doped silicon wafers using both the reflection and transmission techniques. In measuring the reflection and transmission coefficients to determine the complex permittivity by this method, the silicon wafer is sandwiched between two Teflon plates which are quarter-wavelength at mid-band. From the complex permittivity, the resistivity and conductivity can be obtained.

Experimental Work

The research method involved development of a free space microwave measurement system operating in the far-field region employing spot-focusing horn lens antennas and development of computer algorithms to calculate complex permittivity from the measured reflection and transmission coefficients. The general theory of the method was developed by Ghodgaonkar and others [8]. For this free-space measurement set-up, multiple reflections are due to the rectangular to circular waveguide transitions and horn lens antennas. We have implemented a two-port TRL calibration technique along with time-domain gating to remove the effect of multiple reflections. In this method the microwave radiation emitted from the transmitting antenna is focused onto the sample placed at the focal point. Reflections and transmissions from the sample are picked up by the antennas and displayed as S_{11} and S_{21} parameters respectively by the VNA. Dielectric properties of these wafers were determined from the reflection and transmission coefficient data and correlated with resistivity. Even though the set up covers between 8-12.5 GHz but this experiment was carried out between 11-12.5 GHz due to the smaller size of the wafers. By doing so, the errors in S_{11} and S_{21} measurements caused by diffraction of the beam side lobes were minimized. However, the same set-up can be used in the frequency range of 8-40 GHz by appropriate use of mode transitions. The free-space microwave measurement system is schematically illustrated in Figure 1.

Correct function of the free-space microwave measurement was verified by calculating the magnitude and phase of the reflection coefficient, S_{11}, and transmission coefficient, S_{21}, at frequency 8-12.5 GHz. Figures 2

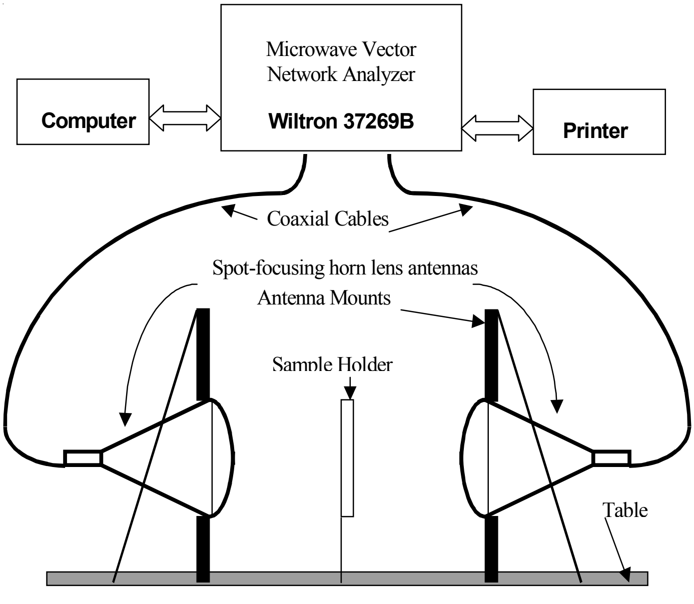

Figure 1: Schematic of Free Space Measurement Set-up

to 5 represent calculated and experimentally measured magnitude and phase of the reflection coefficient, S_{11}, and transmission coefficient, S_{21}. From these figures it can be seen that the angles agree quite well to the theoretical curve except for a slight variation in the magnitudes of S_{11} and S_{21}. This may be caused by experimental inaccuracies, but may also be due to the errors caused by diffraction effects and multiple reflections, which our modeling does not take into account.

Material

Two types of doped silicon semiconductor wafers, namely p-type and n-type were obtained from Helitek Company. Their specifications are shown in the Table 1 below.

Table 1: Specifications for Silicon Wafers

Type / Dopant	N-type	P-type
Diameter (mm)	76.2 ± 0.4	76.2 ± 0.4
Thickness (microns.)	600 ± 25	600 ± 25
Resistivity (ohm-cm)	1 - 100	1 - 100
Orientation	(100)	(100)

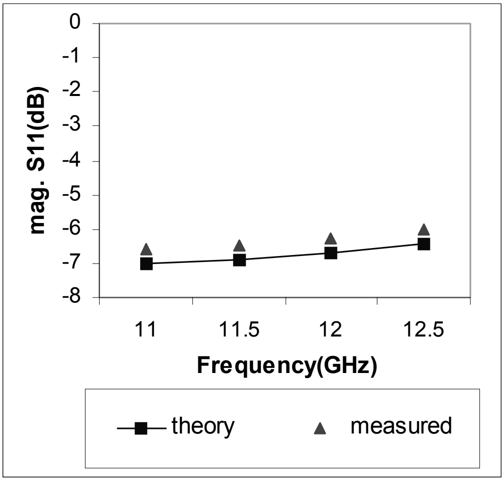

Figure 2: Measured and Calculated Magnitude of S_{11} for Silicon Wafer Sandwiched between Two Quarter-wave Plates

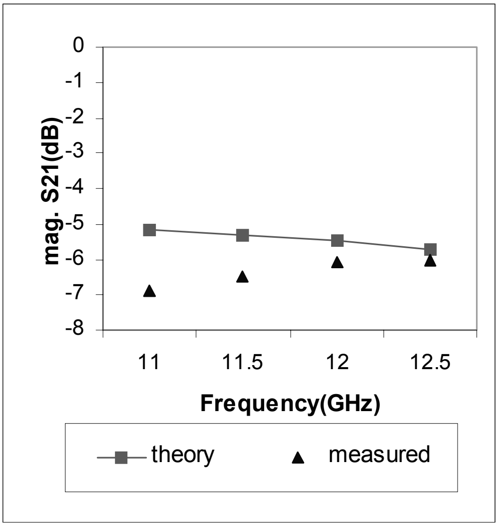

Figure 3: Measured and Calculated Magnitude of S_{21} for Silicon Wafer Sandwiched between Two Quarter-wave Plates

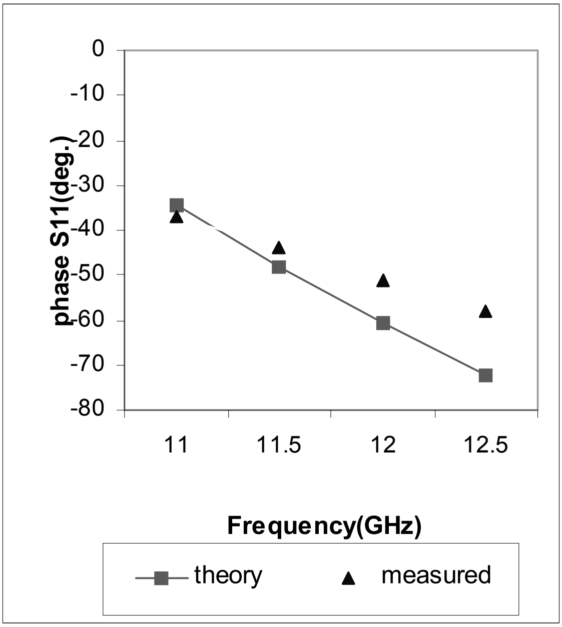

Figure 4: Measured and Calculated Phase of S_{11} for Silicon Wafer Sandwiched Between Two Quarter-wave Plates

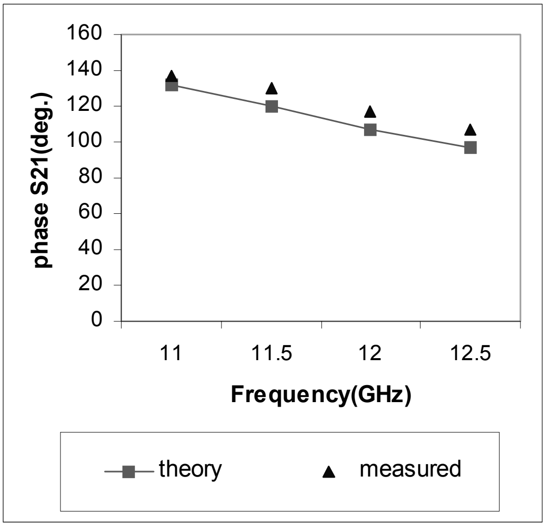

Figure 5: Measured and Calculated Phase of S_{21} for Silicon Wafer Sandwiched Between Two Quarter-wave Plates

Experimental Results

After performing free-space TRL calibration, the through connection was measured. The magnitude and phase of S_{21} was within ± 0.05 dB and ± 0.2° of the theoretical values of 0 dB and 0° respectively, while the error for the S_{11} magnitude and phase for reflect connection was within ±0.2 dB and ±1° of the theoretical values of 0 dB and 180°. For verification a different metal plate was used as a reflect and the result is the magnitude and phase of S_{11} were 0.0 ± 0.1 dB and 180.0 ± 2.0°, respectively.

The measurements were performed on both the shiny (top) and dull (bottom) sides of the silicon wafers. But only the shiny side results are presented since the results are similar. Even though the set up covers between 8-12.5 GHz this experiment was carried out between 11-12.5 GHz due to the smaller size of the wafers. By doing so, the errors in S_{11} and S_{21} measurements caused by diffraction of the beam side lobes were minimized. Using Fortran language, the actual S_{11} and S_{21} of the sample were calculated from the measured S_{11a} and S_{21a} of the Teflon plate-sample-Teflon plate assembly. The plots for the dielectric constant, loss tangent and conductivity are shown in Figures 6-11.

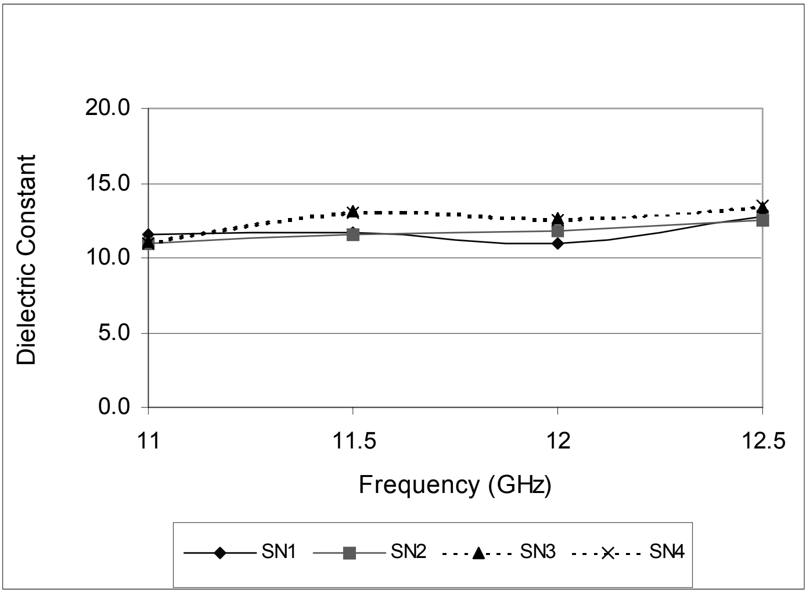

Figure 6: Plot of Dielectric Constant versus Frequency for N-type Wafers

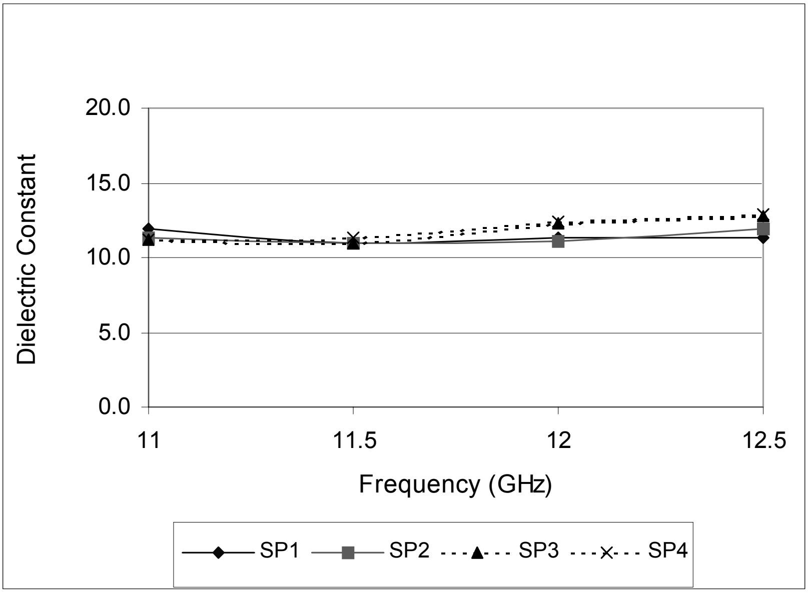

Figure 7: Plot of Dielectric Constant versus Frequency for P-type Wafers

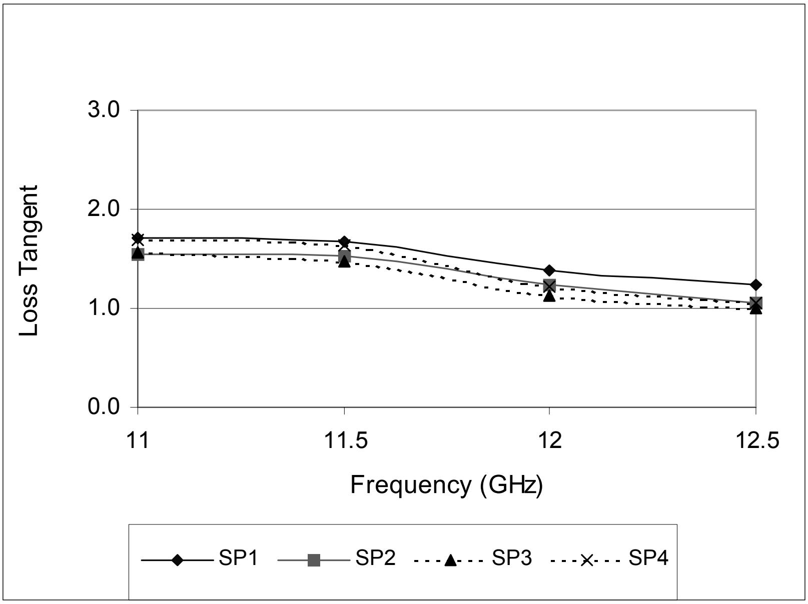

Figure 8: Plot of Loss Tangent versus Frequency for P-type Wafers

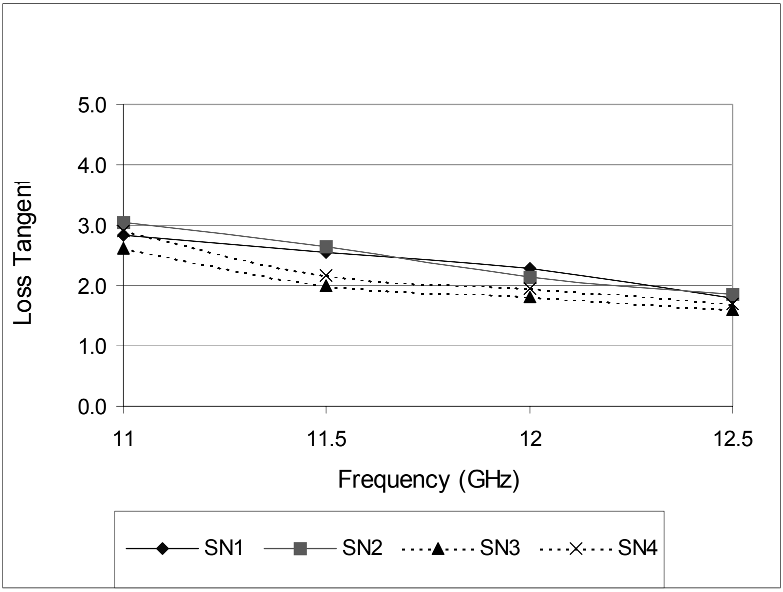

Figure 9: Plot of Loss Tangent versus Frequency for N-type Wafers

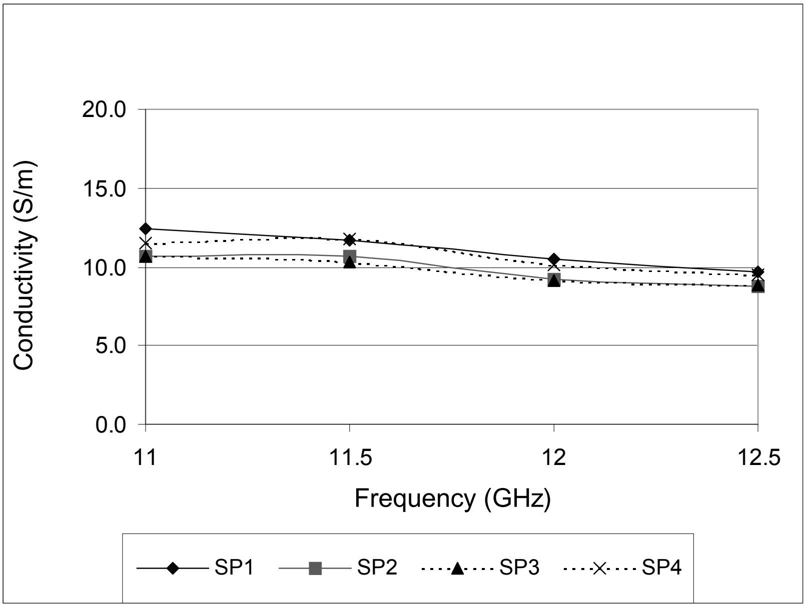

Figure 10: Plot of Conductivity versus Frequency for P-type Wafers

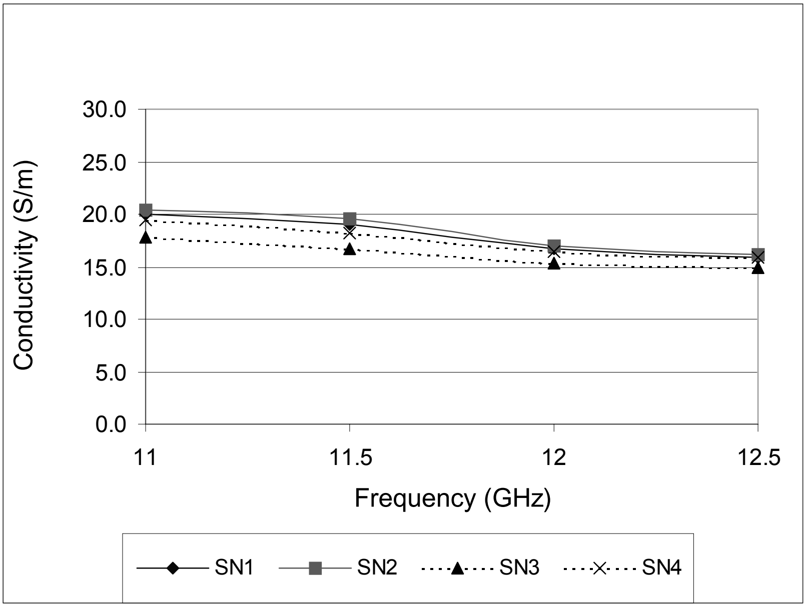

Figure 11: Plot of Conductivity versus Frequency for N-type Wafers

Discussion

From Figures 6 and 7, the measured values of dielectric constant for both p-type and n-type silicon wafers are in the intervals 10.95 to 13.10 and 10.98 to 13.53, respectively. These compare favourably to those reported by Roy *et al.* [6] who obtained values between 11.01 to 11.77 for p-type samples, while Champlin *et al.* [9] quoted figures of 12.41 and 12.27 for n- and p-type respectively. We may relate the wide-range values obtained for the dielectric constant to the errors in the value of the magnitude and phase of the S_{11} and S_{21}, the air-gap effect of the sample assembly and the presence of the free-carriers from the doping material, which modify the characteristic of the wafers.

Figures 8 and 9 give the loss tangent for both the p-type and n-type silicon wafers. The loss tangent turned out to be rather high between 1.00 to 1.90 for p-type and 1.60 to 3.41 for n-type. The result implies that at microwave frequency the doping makes the wafers act like a conductor, absorbing much of the incident power. Therefore high conductivity with high loss exists. Figures 10 and 11 are plots of the conductivity, which show that conductivity decreases with increased frequency. The conductivity obtained is between 8.74 to 13.65 S/m for p-type and 14.95 to 22.93 S/m for the n-type. The presence of the doping material is the contributing factor to this high conductivity and high loss. The resistivity, which is defined as the inverse of conductivity are between 7.33 to 11.40 ohm-cm for p-type and 4.36 to 6.69 ohm-cm for the n-type. The values of resistivity quoted by the wafer manufacturer are between 1 to 100 ohm-cm.

For comparison with microwave resistivity measurements, dc measurements were made by the conventional four-point probe method. The measurements were carried out in the Microelectronics Institute Laboratory in UKM, Bangi. The results presented in Table 2 below show that ac and dc resistivities are within close agreement, as have been reported by Coue *et al.* [5] and Holm *et al.* [6].

Conclusion

A new contactless technique, which gives accurate values of complex permittivity of silicon wafers in the microwave frequency range, is developed. The method yields permittivity of silicon wafers, which are close to those reported in the literature considering the differences in

Table 2: Comparison between AC and DC Resistivity

Sample No.	Microwave Measurement (ohm-cm)	Four-point probe Measurement (ohm-cm)
SN1	5.64	6.07
SN2	5.57	7.13
SP1	9.10	7.64
SP2	10.21	7.77

manufactures, type of silicon semiconductors and frequency ranges. The proposed technique is new for free-space semiconductor characterization and the frequency range covered has not been done previously by other researchers. The technique will be a major contribution to the semiconductor industry. The method is contactless and thus introduces no damage to the samples. This is highly desirable for semiconductor wafers since they are brittle, fragile and need high purity levels. In addition, the technique is fully automated, it will help improve quality of semiconductor characterization while at the same time reduces the time required.

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