MEASUREMENT OF DIELECTRIC CONSTANT AND CONDUCTIVITY OF SILICON WAFERS AT MICROWAVE FREQUENCIES USING A FREE-SPACE METHOD

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1. INTRODUCTION

A contactless and non-destructive microwave method has been developed to characterize silicon semiconductor wafers from reflection and transmission measurement made at normal incidence. 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 of 5mm thickness which act as a quarter-wave transformer at mid-band. The actual reflection and transmission coefficient, S_{11} and S_{21} of the silicon wafers are then calculated from the measured S_{11} and S_{21} by 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 undoped and p-type and n-type doped silicon wafers are reported in the frequency range of 11 – 12.5 GHz.

The choice of substrate material is important for the high frequency integrated circuits design. Besides substrate thickness and strip width, substrate permittivity is another important parameter for high frequency IC design. Therefore knowledge of these properties will contribute significant understanding and ultimately will assist high frequency IC designers. By conventional characterization methods, the probes are in direct contact with the samples thus inducing probe damage, contaminations and contact noise during measurement. Several methods for measuring microwave permittivity and conductivity of semiconductor materials have been reported [1-3].

2. THEORY

The general theory of the method is well established in the literature [4]. By applying boundary conditions at the air-sample interfaces, it can be shown that the S_{11} and S_{21} parameters are related to the reflection coefficient Γ and transmission coefficient T by the following equations:

$$S_{11} = \frac{\Gamma(1-T^2)}{1-\Gamma^2 T^2} \qquad (1)$$

$$S_{21} = \frac{T(1-\Gamma^2)}{1-\Gamma^2 T^2} \qquad (2)$$

where Γ, the reflection coefficient of the air-sample interface, and T are given by

$$\Gamma = \frac{(Z_{sn}-1)}{(Z_{sn}+1)} \qquad (3)$$

$$T = e^{-\gamma d} \qquad (4)$$

In (3) and (4), Z_{sn} and γ are the normalized characteristic impedance and propagation constants of the sample. They are related to ε* and μ* by the following relationships:

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$$\gamma = \gamma_0 \sqrt{\varepsilon^* \mu^*} \qquad (5)$$

$$Z_{sn} = \sqrt{\frac{\mu^*}{\varepsilon^*}} \qquad (6)$$

Where $\gamma_0 = (j2\pi / \lambda_0)$ represents the propagation constant of free space, and λ_0 is the free-space wavelength. From (1) and (2), Γ and T can be written as

$$\Gamma = K \pm \sqrt{K^2 - 1} \qquad (7)$$

Where

$$K = \frac{S_{11}{}^2 - S_{21}{}^2 + 1}{2S_{11}} \qquad (8)$$

$$T = \frac{S_{11} + S_{21} - \Gamma}{1 - (S_{11} + S_{21})\Gamma} \qquad (9)$$

Using (4), the complex propagation constant γ can be written as

$$\gamma = [\log_e (1/T)]/d \qquad (10)$$

From (3) and (6),

$$\sqrt{\frac{\mu^*}{\varepsilon^*}} = \left(\frac{1+\Gamma}{1-\Gamma}\right) \qquad (11)$$

From (5) and (11), we obtain

$$\varepsilon^* = \frac{\gamma}{\gamma_0}\left(\frac{1-\Gamma}{1+\Gamma}\right) \qquad (12)$$

Since the parameter T in (10) is a complex number, there are multiple values for γ given by

$$\gamma = [\log_e (1/T)]/d + j\left[\frac{2\pi n - \phi}{d}\right] \qquad (13)$$

For $n = 0$ and $-2\pi < \phi < 0$, (d / λ_m) is between 0 and 1. If the sample thickness d is chosen such that it is less than λ_m, then (7) ~ (12) will give a unique value of ϵ^* which corresponds to $n = 0$. For $d > \lambda_m$ ambiguity in ϵ^* can be resolved by making measurements on two different thickness of the sample.

The quarter-wave transformer is used as impedance inverter to improve the accuracy of the S_{11} and S_{21} measurements. The actual S_{11} and S_{21} of the sample can be calculated from the measured S_{11a} and S_{21a} using ABCD matrix because the complex permittivity and thickness of the teflon plates are known. If the ABCD matrix of the assembly is denoted as $[A^a]$, the sample $[A^s]$ and the teflon $[A^t]$, then following relationship is obtained [4]

$$[A^s] = [A^t]^{-1} \cdot [A^a] \cdot [A^t]^{-1} \qquad (14)$$

And the parameters S_{11} and S_{21} of the sample can be obtained using the following expressions:

$$S_{11} = \left[\frac{A^s + B^s - C^s - D^s}{A^s + B^s + C^s + D^s}\right] \qquad (15)$$

$$S_{21} = \left[\frac{2}{A^s + B^s + C^s + D^s} \right] \qquad (16)$$

3. MEASUREMENT SET UP

The measurement system consists of a pair of spot-focusing horn lens antenna connected to two ports of the Wiltron 37269B Vector Network Analyzer by using circular to rectangular waveguide adapters, rectangular waveguide to coaxial line adapters, and precision coaxial cables [4]. We have implemented free-space TRL calibration technique by establishing three standards, namely, a through connection, a short circuit connected to each port and a transmission line connected between the test ports. This calibration along with time domain gating can eliminate effects of multiple reflections.

Because of spot focusing action of antennas at the focus, the diffraction effects are negligible if the minimum transverse dimension of the sample is greater than three times the 3-dB E-plane beam width (which is approximately 3 λ_0). It is observed that in case of small sample size such as the undoped wafers, the edge diffraction errors can be minimised using time domain gating and with the use of a metal plate window with opening same as the sample during the thru and line calibration.

Results of the magnitude and phase of S_{11} are within ± 0.2 dB and $\pm 1^o$ of the theoretical value of 0 dB and 180^o for the metal plate. For the through connection, the measured magnitude and phase of S_{21} are within ± 0.05 dB and $\pm 0.2^o$ of the theoretical values of 0 dB and 0^o.

4. RESULTS AND DISCUSSION

The measurements were performed on doped and undoped silicon wafers. The n-type and p-type are 0.60 mm thickness with diameter 76 mm and (100) orientation. While the undoped samples are 0.43 mm thickness with diameter 50 mm. Figure 1 and 2 give the dielectric constant for both samples with results ranging between 11.00 to 13.04. Silicon has a dielectric constant of 11.8 at microwave frequencies [3]. The wide range values obtained in this method may be due to measurement errors in S_{11} and S_{21} and gap effect of the sample assembly. The doped samples have loss tangent between 1.10 to 2.77 which is considered high loss due to the dopant in the wafers which acted like a conductor absorbing much of the incident power. The loss tangent for the undoped samples were between 0.003 to 0.18 which is low loss, could be due to presence of some impurity since intrinsic silicon is hard to get.

From the measured results, the conductivity of the silicon wafers can be obtained by the following relationship

$$\sigma = \omega\varepsilon_0 \varepsilon'' = 2\pi f \varepsilon_0 \varepsilon''$$

where ε_0 is 8.854×10^{-12} Farad/meter and ε'' is the imaginary part of the complex permittivity.
Figure 3 and 4 are plots of the conductivity which show a trend of decrease conductivity with increased frequency. The values were between 8.9 to 19.6 S/m for the doped samples and 3.4×10^{-2} to 14.4×10^{-1} S/m for undoped samples. Conductivity of pure silicon is about 3.9×10^{-4} S/m. The presence of the doping material is the contributing factor to this high conductivity. DC measurements were made by the four-point probe method, and a dc conductivity between 13.5 to 16.4 S/m were measured for the doped samples. The results show that ac and dc conductivity are within close proximity which have been reported by Coue *et al.* [2] and Holm *et al.* [5].

5. CONCLUSION

A new contactless method which gives accurate values of dielectric constant and conductivity of silicon wafers in the microwave frequency range is developed. The accuracy is improved by utilizing a quarter-wave transformer and yields results which are comparable to published values.

REFERENCES

[1] Roy, P.K., Datta, A.N., "Application of Quarter-Wave Transformer for Precise Measurement of Complex Conductivity of Semiconductors", *IEEE Trans. on Microwave Theory and Techniques*, vol. 37, pp.144-146, Feb. 1974.

[2] Coue, E., Chausse, J.P., "Microwave Method for Electrical Measurements of Semiconductors: Theory and Measurements", *Semiconductor Science and Technology*, vol. 15, No.2, pp.178-183, Feb. 2000.

[3] J. Musil and F. Zacek, *Microwave Measurements of Complex Permittivity by Free-Space Methods and Their Applications,* New York:Elsevier, 1986, pp. 168-174, 260.

[4] D.K Ghodgaonkar, V.V Varadan and V.K. Varadan, "Free Space Measurement of Complex Permittivity and Complex Permeability of Magnetic Materials at Microwave Frequencies", *IEEE Trans. of Inst. and Measurement*, Vol.39, pp.387-394, April 1990.

[5] Holm, J.D., and Champlin K.S., "Microwave conductivity of silicon and germanium", *J. Appl. Phys.,* vol. 39, pp. 275-284, Jan. 1968.

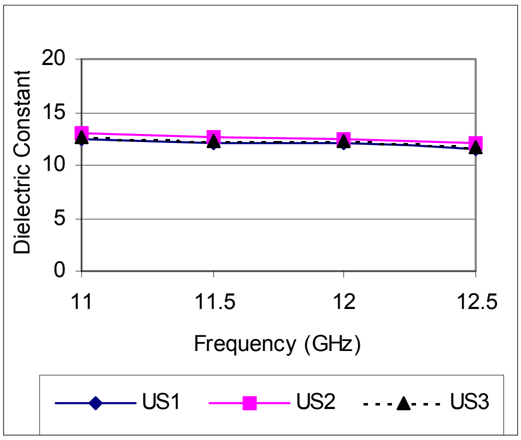

Figure 1: Undoped silicon dielectric constant

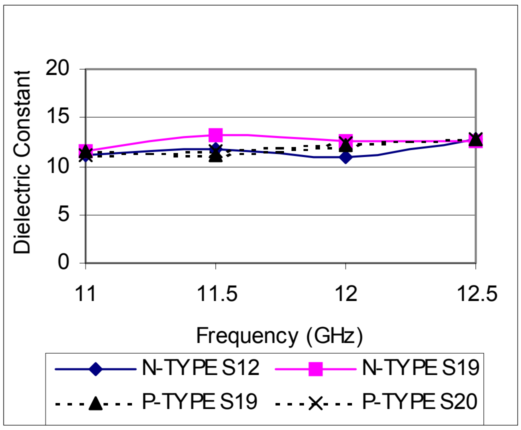

Figure 2: Doped silicon dielectric constant

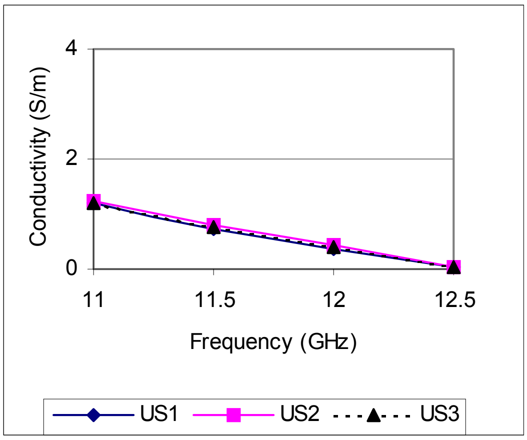

Figure 3: Undoped silicon conductivity

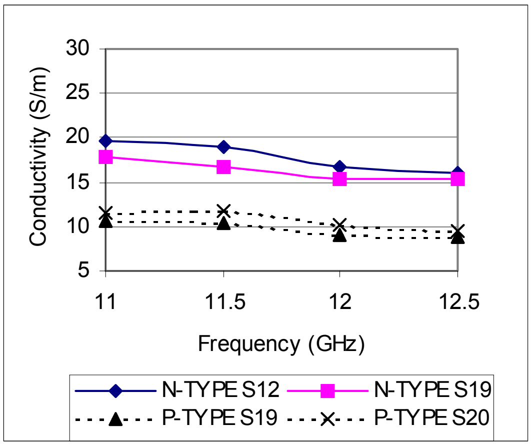

Figure 4: Doped silicon conductivity