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Millimeter Wave Technique for Non-destructive Characterization of Material Homogeneity

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Introduction

It is well known that millimetre waves can be used for non-destructive characterization of a wide spectrum of materials. Usually the bulk or surface resistance as well as the dielectric constant of the material can be measured in this way. In many cases, the quality of the fabricated material depends on spatial distribution of these parameters in the whole area of the sample. This is especially important for large area dielectric substrates and thin films used in electronics. Relatively short wavelength of the millimetre wave provides the possibility to utilise them for non-destructive homogeneity characterization of materials. The method based on the scanning of the material surface by millimeter wave beam and the measurement of reflected (transmitted) power has been suggested yielding a resistivity map [1]. The probe size and the probe-sample distance determine the spatial resolution of the method. Several designs of the millimeter wave probes based on a narrow resonant slit [1], metal micro-slit [2] and thin-slit aperture in a convex end plate of rectangular waveguide [3] were used. A non-destructive millimeter wave resonant measurement method based on the open resonator technique for the homogeneity characterization of dielectric [4], high-temperature superconductor wafers [5] was also proposed. Although the sensitivity of this method is very high, its spatial resolution that depends on the millimeter wave beam aperture (∅ ~ 7 mm) is not sufficiently good. In this paper we propose a millimeter wave technique that is capable of solving this problem.

Theoretical background

It is known that electromagnetic wave transmitted through a dielectric plate demonstrates resonance character. Maximum of transmission is observed at the condition $d/\lambda = 1/2, 1, 3/2, 2, \ldots n/2$, where d is a thickness of the plate, λ is a wavelength, n is an integer. This resonance is known as Fabry-Perot resonance. An analysis of electromagnetic wave transmission through the dielectric plate with losses was presented recently [6]. Typical calculated dependences of transmitted wave coefficient and phase for different values of plate conductivity σ are presented in Fig. 1. The conductivity of the plate in the figure is characterized by the dimensionless parameter $\xi = Z_0\sigma d/2$, where Z_0 is an impedance of the free space, and σ is conductivity. When the thickness of the plate contains whole number of half-waves the Fabry-Perot resonance condition is fulfilled and the transmitted wave power reaches its maximum. When σ increases the transmitted wave power decreases. It is important to point out that the influence of the conductivity on the transmitted wave phase is negligible. It is seen from the lower part of the figure where the dependences of the phase for different values of ξ are presented. The largest influence on the transmitted wave phase has a dielectric constant ε of the material under test. Its change causes the strongest shift of the transmitted wave phase at the same Fabry-Perot condition [7]. It means that the largest sensitivity determining inhomogeneities of the dielectric constant and conductivity in semiconductor wafer can be obtained by measuring transmission coefficient and phase distribution at Fabry-Perot resonance conditions. Therefore wishing to determine both dielectric constant and conductivity variation in the wafer area the phase and amplitude views in transmitted wave at a resonance condition should be analysed.

Measurement technique

The main idea of the measurement technique operation is the local excitation of millimeter waves in the sample under test and the measurement of transmitted (reflected) wave amplitude and phase at different points of the sample. In essence, we use a millimeter wave bridge consisting of a reference signal and a measuring signal channels (Fig. 2). The tested sample is placed between special waveguide probes that provide both local excitation and reception of the low power millimeter wave signals. The sample can be moved relative to the exciting and receiving probes by scanning mechanism. Changes of the electric or dielectric parameters in the sample area cause changes in the amplitude and phase of the transmitted (reflected) signal. By probing the sample at different points with the millimeter wave beam, information about the homogeneity of the sample can be obtained. All measurement processes are computer controlled and the measurement results are compiled in the computer. Some examples of the applications of our technique for homogeneity measurement of dielectric and semiconductor wafers are presented below.

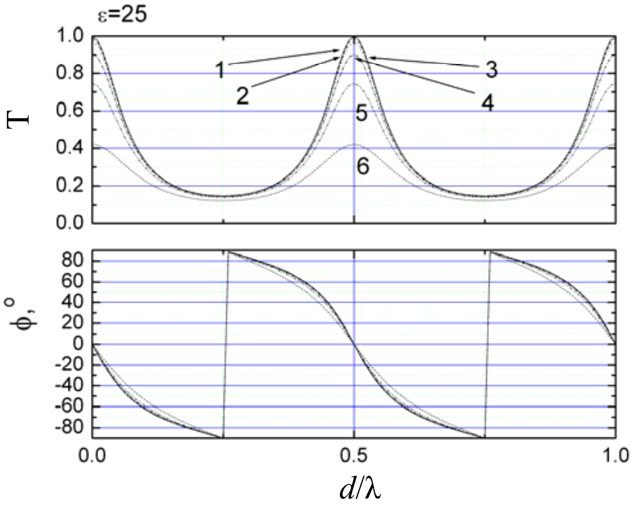

Fig. 1. Typical dependences of the transmission coefficient (top) and the phase (bottom) of wave transmitted through the dielectric plate (ε=25) with losses on its thickness normalized to the wavelength of the plate for different values of dimensionless parameter ξ characterizing conductivity of the plate. 1– ξ=0, 2 – ξ=0.01, 3 – ξ=0.03, 4 – ξ=0.1, 5 - ξ=0.3, 6 – ξ=1.0

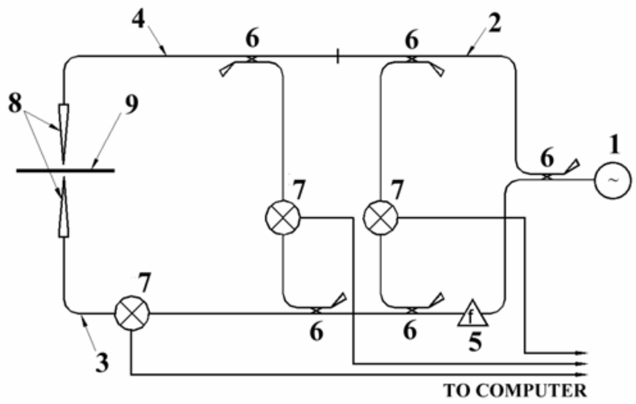

Fig. 2. Schematic diagram of the device measuring transmitted and reflected electromagnetic wave amplitude and phase: 1 is millimeter wave oscillator, 2 is reference signal channel, 3 is transmitted signal channel, 4 is reflected signal channel, 5 is frequency converter, 6 are directional couplers, 7 are mixers, 8 are antennas, and 9 is the sample under test

Measurement results

Semiconductor Si and dielectric $LaAlO_3$ wafers have been used for material homogeneity measurement tests. Measurements were performed in the frequency range 120 – 150 GHz. Open end sections of circular waveguide were used for local excitation and reception of millimeter waves. A spacing between the end of the waveguide and sample surface was roughly 0.2 mm. Scanning of the sample was performed using two step motors. One of them serves for the sample rotation and the other one provides its linear motion. Therefore, the scanning process is going on the helix way (Fig. 2) covering all surface of the sample.

Measurement results are presented in Fig. 3 to Fig. 5. The distribution of the amplitude and phase of the wave transmitted trough the homogeneous Si wafer is shown in Fig. 3. It is seen that both the amplitude and phase distributions are rather homogeneous as well. Measured amplitude and phase variations within sample are less than 0.2 dB and 2°, respectively It seems that these values are the limits of the sensitivity of the present-day device.

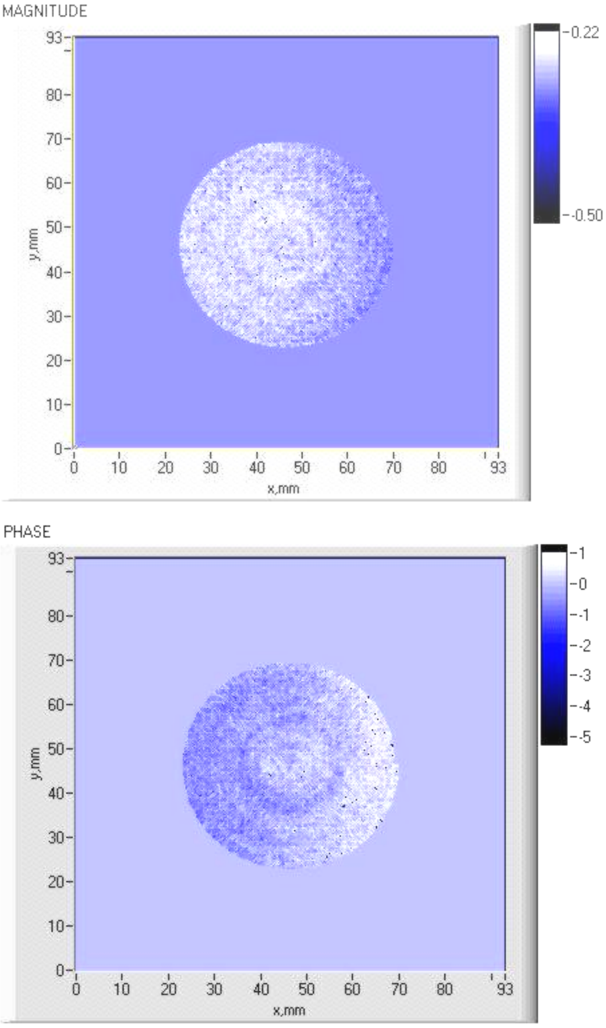

Fig. 3. Millimeter wave amplitude (top) and phase (bottom) images of the Si wafer. Wave frequency is f = 130 GHz. Thickness of the wafer is 0.30 mm

More significant variation of the amplitude and phase has been observed in the corresponding images for $LaAlO_3$

wafer (Fig. 4 and Fig. 5). They can be related to the dielectric constant inhomogeneous distribution in the volume of the wafer occurring due to twinning imperfections that are common for this type of material [8]. Comparing images shown in Fig. 4 and Fig. 5 that are measured at *f* =120 GHz and *f* =150 GHz, respectively, one can see that in the latter image smaller changes of the transmitted wave amplitude and phase are observed. The point is that for $LaAlO_3$ ($\varepsilon = 25$) wafer second order Fabry-Perot resonance condition ($d = \lambda$) is fulfilled at *f*=120 GHz. As for *f* =150 GHz, d = 5/4 λ and this frequency is far enough from the resonance. Analyzing the phase images for both frequencies, one can see that the largest change in the phase angle is roughly 30° for the frequency *f* =120 GHz whereas at higher frequency where the condition for Fabry-Perot resonance is not satisfied the variation of the phase is only 4°. These results confirmed in general our earlier predictions that the largest sensitivity of homogeneity mapping can be achieved when the measurements are performed at Fabry-Perot resonance conditions.

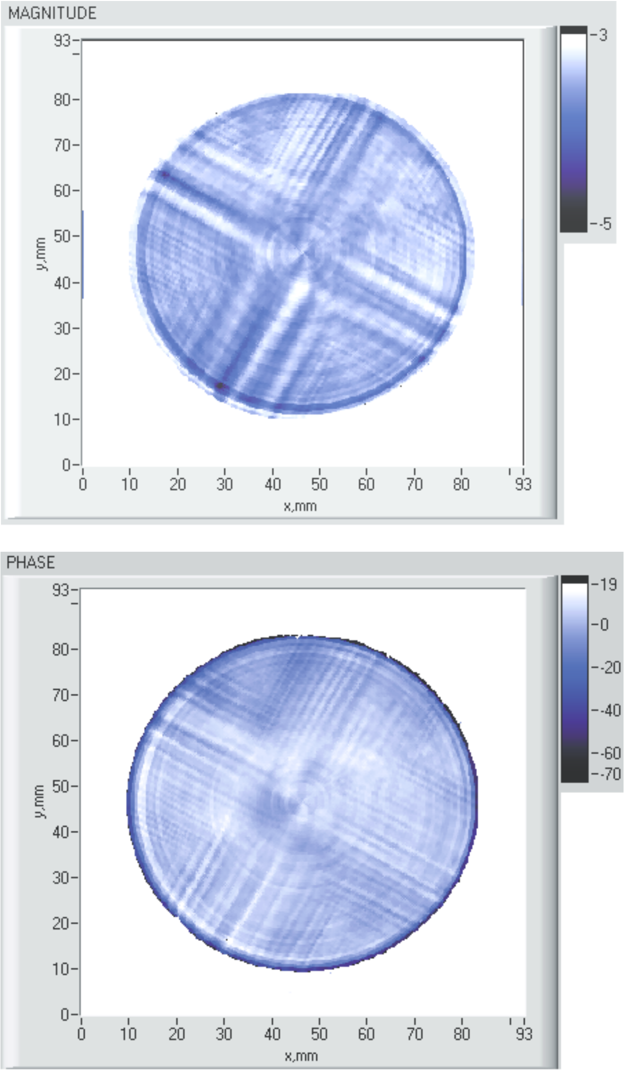

Fig. 4. Millimeter wave amplitude (top) and phase (bottom) images of the $LaAlO_3$ wafer at frequency 120 GHz. The thickness of the wafer is 0.52 mm

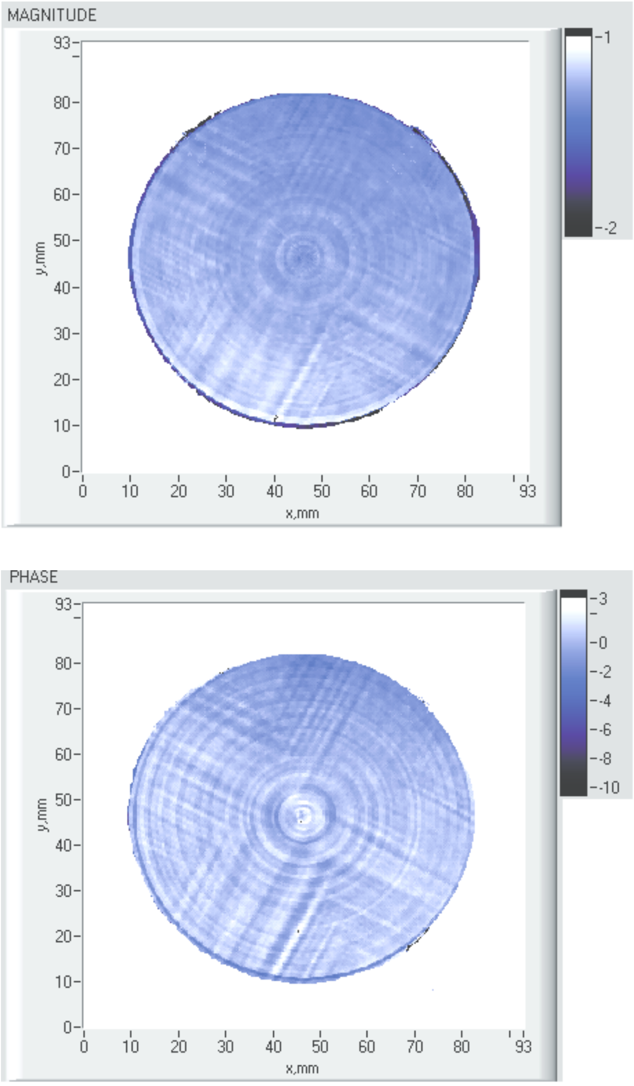

Fig. 5. Millimeter wave amplitude (top) and phase (bottom) images of the $LaAlO_3$ wafer at frequency 150 GHz. The thickness of the wafer is 0.52 mm

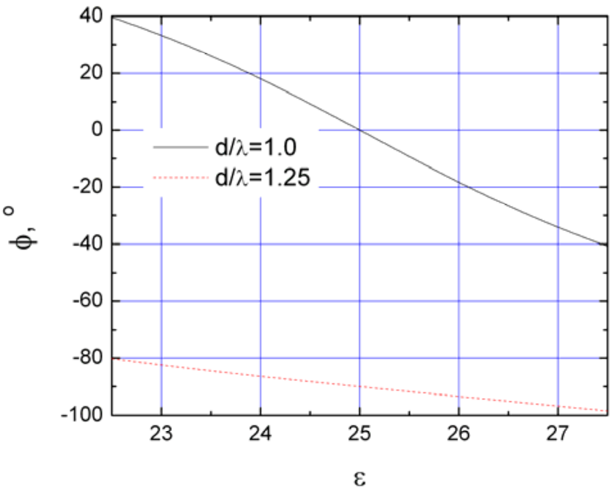

Fig. 6. Calculated dependences of the phase shift on the dielectric constant for $LaAlO_3$ wafer used in measurements for *f* =120 GHz frequency (solid line) and for *f* =150 GHz (dashed line)

Calculated dependencies of the phase shift on the dielectric constant for $LaAlO_3$ wafer at frequencies that correspond to the measurement results are shown in Fig. 6. Making use of these dependencies and experimental data one can estimate that experimentally observed phase variation corresponds to 8 % change of the dielectric constant. It is worthwhile to mention that similar value of dielectric constant variation has been determined from the measurement results performed earlier using dielectric filed resonant cavity method [8].

Conclusion

Millimeter wave bridge technique for nondestructive material homogeneity characterization is presented. The idea of this technique is the local excitation of the millimeter waves in the wafer under test and the measurement of the transmitted wave amplitude and phase in the different places of the sample. Measurement results of the homogeneity measurements for semiconductor and dielectric wafers are presented. The space resolution is about 1 mm^2. The measurement technique sensitivity is discussed.

Acknowledgment

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Millimeter wave bridge technique for nondestructive material homogeneity characterization is described. The idea of this technique is the local excitation of the millimeter waves in the testing material and the measurement of the transmitted wave amplitude and phase in different places of it, i.e. the material plate is scanned by the beam of the millimeter waves. Same results of the homogeneity measurements for semiconductor and dielectric wafers are presented. The measurement technique sensitivity is discussed. Ill. 6, bibl. 8 (in English; summaries in English, Russian and Lithuanian).

А. Лауринавичюс, Ж. Канцлерис, Т. Анбиндерис, О. Мартянова, Ю. Пришутов. Техника миллиметровых волн для неразрушающего контроля материалов // Электроника и электротехника. – Каунас: Технология, 2006. – № 7(71). С. 59–62.

Описана техника миллиметровых волн, предназначеная для неразрушающего контроля материалов. Принцип её действия основан на локальном возбуждении миллиметровых волн в исследуемой пластине материала и измерении амплитуды и фазы прошедшей через неё волны, т. е. пластина сканируется лучём миллиметровой волны. Представлены некоторые результаты измерения однородности полупроводниковой и диэлектрической пластин. Обсуждена чувствителность измерительной техники. Ил. 6, библ. 8 (на английском языке; рефераты на английском, русском и литовском яз.).

A. Laurinavičius, Ž. Kancleris, T. Anbinderis, O. Martianova, J. Prišutov. Neardomoji medžiagų homogeniškumo kontrolė naudojant milimetrinių bangų techniką // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2006. – No. 7(71). – P. 59–62.

Aprašyta neardomosios medžiagų homogeniškumo kontrolės matavimo metodika ir prietaisas, veikiantis milimetrinių bangų tiltelio principu. Pagrindinė matavimo metodikos idėja yra ta, kad milimetrinės bangos yra lokaliai žadinamos tiriamosios medžiagos plokštelėje ir matuojama praėjusios bangos amplitudė ir fazė skirtingose jos vietose, t. y. plokštelė skenuojama milimetrinių bangų spinduliu. Pateikti puslaidininkinės ir dielektrinės plokštelių homogeniškumo matavimo rezultatai. Taip pat aptartas matavimo prietaiso jautris. Il. 6, bibl. 8 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).