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Microwave and RF methods of contactless mapping of the sheet resistance and the complex permittivity of conductive materials and semiconductors*

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Abstract

Split-post dielectric-resonator and eddy current methods have been compared for the sheet resistance and resistivity mapping of semiconductor wafers and thin conducting films deposited on semi-insulating substrates. It has been shown that both methods give similar measurement results for the sheet resistance values that lie within their measurement ranges. Split-post dielectric-resonator and eddy current techniques can be used for measurements on samples having similar size. Measurements that employ a split-post dielectric resonator allow measurement of about three orders of magnitude larger sheet resistance values (especially for thin films) than the eddy current method but they are more complicated than the RF method and require additional microwave equipment to measure the Q -factors and the resonance frequencies.

Keywords: resistivity mapping, semiconductors, thin metal films, sheet resistance, conductivity

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Several contactless techniques for resistivity measurements exist that allow non-destructive testing of semiconductors. One of them is the technique, developed by Miller *et al* [1], that utilizes radio-frequency-free-carrier power absorption and is used in commercially available instruments operating at RF frequencies [2]. Physically, this technique utilizes absorption of RF eddy current power induced by an emitter coil in a semiconductor layer. The typical measurement range for this technique is 10^{-3} – 10^3 Ω cm.

Time domain charge measurements (TDCM) are achieved with the time-dependent capacitive measurement technique.

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TDCM have been implemented for contactless mapping of resistivity [3] and are applicable for on-wafer measurements of semi-insulating materials having resistivities in the range 10^5 – 10^{12} Ω cm. Alternatively to the RF and TDCM methods microwave techniques can be used to measure the resistivity and sheet resistance of conducting films. In the last few years split-post and single-post dielectric resonators have been developed for contactless resistivity measurements in the range 10^{-5} – 10^5 Ω cm. These methods have already been applied for the measurements of semiconductor wafers [4], thin metal films [5, 6], conductive polymer films [7], graphene and epitaxial SiC layers deposited on semi-insulating SiC substrates [8] and planar metamaterials (metal-dielectric) [6]. This paper is devoted to the comparison of RF and microwave techniques intended for sheet-resistance mapping instruments.

2. Microwave permittivity and conductivity

In general, the complex permittivity of an isotropic semiconductor material is given by the following equation:

$$\varepsilon = \varepsilon_0 \left(\varepsilon_r - j\varepsilon_r'' - j\frac{\sigma}{\omega\varepsilon_0} \right) = \varepsilon_0\varepsilon_r(1 - j\tan\delta), \quad (1)$$

where $\tan\delta$ is the effective dielectric loss tangent of the semiconductor given by

$$\tan\delta = \tan\delta_d + \frac{\sigma}{\omega\varepsilon_0\varepsilon_r} = \tan\delta_d + \tan\delta_c, \quad (2)$$

where ε_0 is the permittivity of vacuum, ε_r is the relative real permittivity of the semiconductor, ω is the angular frequency, σ is the conductivity, $\tan\delta_d$ is the dielectric loss tangent associated with pure dielectric loss mechanisms (e.g. electronic and ionic polarization), and $\tan\delta_c$ is the dielectric loss tangent associated with pure conductor loss mechanisms.

Dielectric loss tangent of any material describes quantitatively dissipation of the electric energy due to different physical processes such as electrical conduction, dielectric relaxation, dielectric resonance and loss from nonlinear processes. When we measure the loss of a certain material at a single frequency we cannot, in general, distinguish between them. They all give rise to one measurable quantity, namely the total measured dielectric loss tangent. High purity large energy gap semiconductors such as SiC, GaAs or GaP at room temperatures are semi-insulating. The dielectric loss tangent due to dielectric losses of GaAs and GaP is smaller than 2×10^{-4} at frequencies smaller than 10 GHz at room temperature [9]. The dielectric loss tangent of SiC at the same frequency and temperature range is well below 10^{-4} . For silicon, it is impossible to manufacture a material of such quality that the dielectric losses will be dominant over the conductor losses [10]. For this reason it is very difficult to determine pure dielectric losses in Si at microwave frequencies at room temperature.

One limited possibility of distinguishing between dielectric and conductor losses in high resistivity semiconductors is to perform measurements at two significantly different frequencies, e.g. at 5 and 10 GHz. As is seen from formula (2), the dielectric loss tangent due to conductor losses decreases with frequency. Experiments with semi-insulating semiconductors show that the dielectric loss tangent due to pure dielectric losses slightly increases with frequency. If for a given sample decrease of the total dielectric loss tangent is observed, that would mean that the conductor loss mechanism dominates in it.

3. Split- and single-post dielectric-resonator techniques

Split-post dielectric resonators (SPDRs) intended for measurements of permittivity and the dielectric loss tangent of dielectrics are commercially available for a number of operational frequencies from 1.1 to 20 GHz. Their size and therefore the size of samples that can be measured in them depends on frequency. Generally the larger the frequency, the smaller the resonator, and the smaller

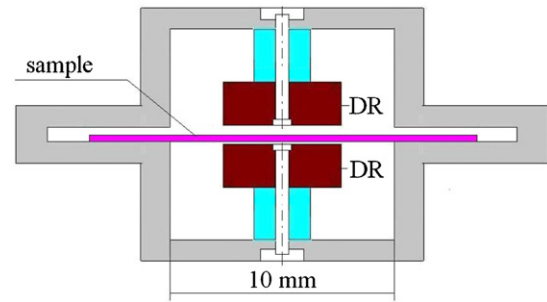


Figure 1. Split-post dielectric-resonator (12 GHz) intended for sheet resistance (R_s) and resistivity mapping. Abbreviation DR means dielectric resonator.

the minimum lateral size of the sample. On the other hand, the maximum thickness of the sample that can be inserted in SPDR decreases with frequency. The resonance frequency shift due to the presence of the sample is proportional to the product of the thickness and the electric susceptibility of the sample. It must be limited due to the possible appearance of spurious modes and electromagnetic energy leakage through the edges of the sample. In sheet resistance mapping instruments it is desirable to have as small a diameter of SPDR as possible, but on the other hand some semiconductor wafers, or substrates, would have the thickness of the order of 1 mm and permittivity of the order of 10. For these reasons the optimum frequency range for SPDRs intended for mapping instruments is from 5 to 12 GHz. The SPDR operating at 5 GHz would allow us to measure semiconductor wafers having thickness up to 1.2 mm with a minimum sample area of 20 mm \times 20 mm, while the SPDR operating at 12 GHz would allow us to measure samples having thickness up to 0.5 mm with a minimum sample area of 10 mm \times 10 mm.

The SPDR operating at 12 GHz is schematically depicted in figure 1. Sheet resistance measurement limits for this resonator are as follows. The minimum sheet resistance value which can be determined is 1.7 k Ω /square. It is related to the minimum measurable Q -factor value of SPDR ($Q = 100$). The maximum sheet resistance value that can be determined is 8 M Ω /square (this limit is valid for thin conducting films deposited on semi-insulating substrates). It corresponds to 2% change of Q -factor due to the presence of conducting film. The maximum thickness of the substrate (or wafer) is 0.5 mm for the relative permittivity of the substrate $\varepsilon_s = 12$ and 1 mm for $\varepsilon_s \leq 6$. The minimum lateral size of the sample is 10 mm \times 10 mm. The electric field and the electric energy distribution in 12 GHz SPDR are shown in figures 2 and 3.

It is seen that the electric energy spot in the sample (area where more than 95% of the electric energy is concentrated) has a diameter of about 5 mm. It should also be mentioned that the current density in the high resistivity samples measured in SPDRs is almost constant along the thickness of samples. It should also be underlined that SPDRs are intended for measurements of the complex permittivity, so for semiconductors having large surface resistance values their permittivity determination is straightforward, provided that the thickness of the sample is known. Alternatively,

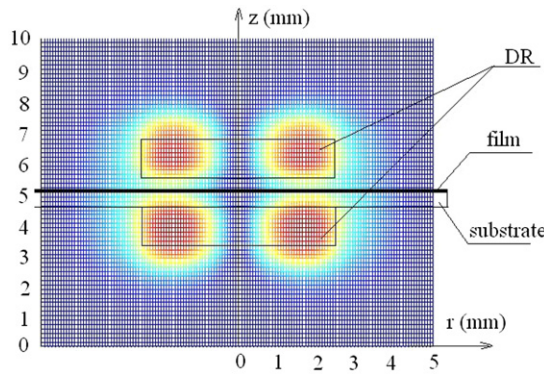


Figure 2. Electric field distribution in a cross section of the 12 GHz split-post dielectric resonator.

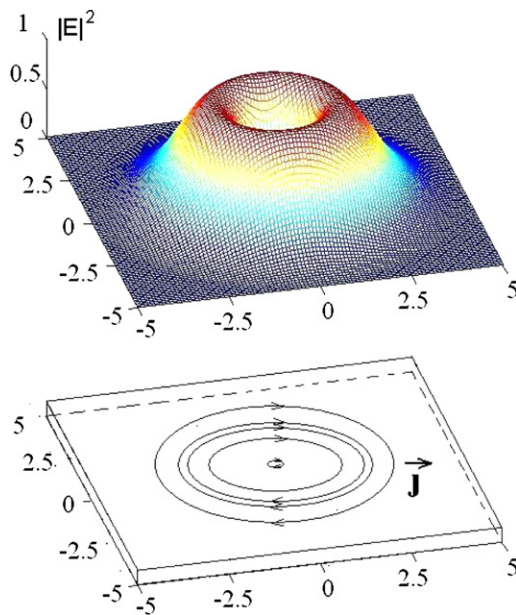


Figure 3. Electric energy and currents in a 10 mm × 10 mm sample for the 12 GHz split-post dielectric resonator.

assuming that for the given semiconductor the real part of the complex permittivity (dielectric constant) is known, one can

very precisely determine and map the thickness of the sample. Therefore SPDRs can be employed not only for the sheet resistance mapping but also for permittivity (or thickness) mapping of semiconductor wafers. Examples of resistivity and thickness mapping with 4.8 GHz SPDR on large diameter (6 inches) high resistivity Si samples are shown in figures 4 and 5.

The sheet resistance and conductivity of thin highly conducting materials can be conveniently measured employing single-post dielectric resonators, e.g. such as that depicted in figure 6 [8].

The presence of a conductive film under test which is situated away from the metal surface of the cavity produces changes of the resonance frequency and Q -factor of the resonator. These changes depend predominantly on the product of the conductivity and film thickness, and are shown in figures 7(a) and (b) [6]. Physical reasons for such dependences of the Q -factors and the resonance frequency shifts on σh (surface conductivity) are described in detail in [8]. One can observe that from the measured resonance frequency and Q -factor, one can uniquely determine the surface conductivity value in the range $0.0001 \text{ S} < \sigma h < 10 \text{ S}$, which corresponds to the surface resistance values in the range $0.1 \text{ } \Omega/\text{square} < R_s < 10\,000 \text{ } \Omega/\text{square}$. Materials having lower surface resistance values (even superconductors) can still be measured employing the sapphire dielectric-resonator technique [5]. It should be pointed out that for materials having small sheet resistance values (below $10 \text{ } \Omega/\text{square}$), it is impossible to determine the real part of their permittivity.

4. RF sheet resistance mapping

The eddy current measurement technique for semiconductors was developed by Miller *et al* at Bell Labs [1]. Later on Leighton Electronics Inc. licensed the technology and manufactures sophisticated test equipment that includes resistivity/sheet resistance measurements for compound semiconductors, silicon and flat panel displays [2].

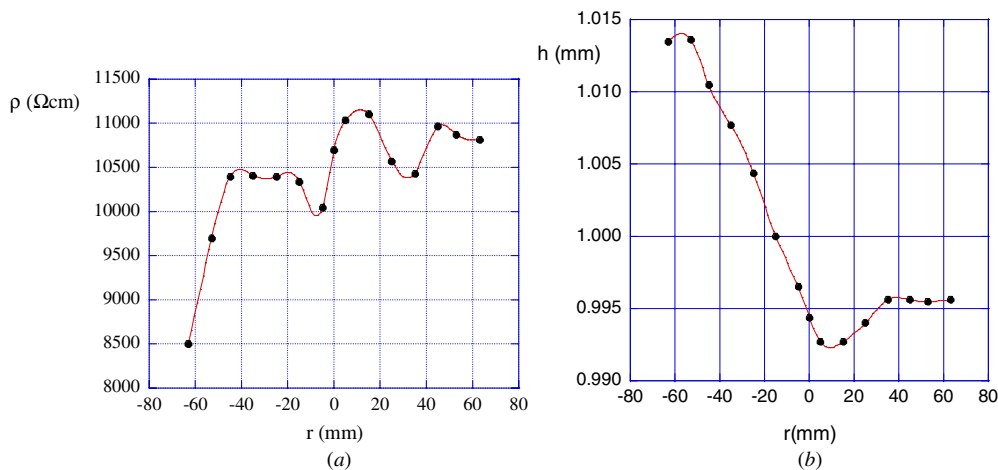


Figure 4. Mapping of resistivity (a) and thickness (b) along the diameter of a high resistivity reference Si sample numbered HR-Si1.

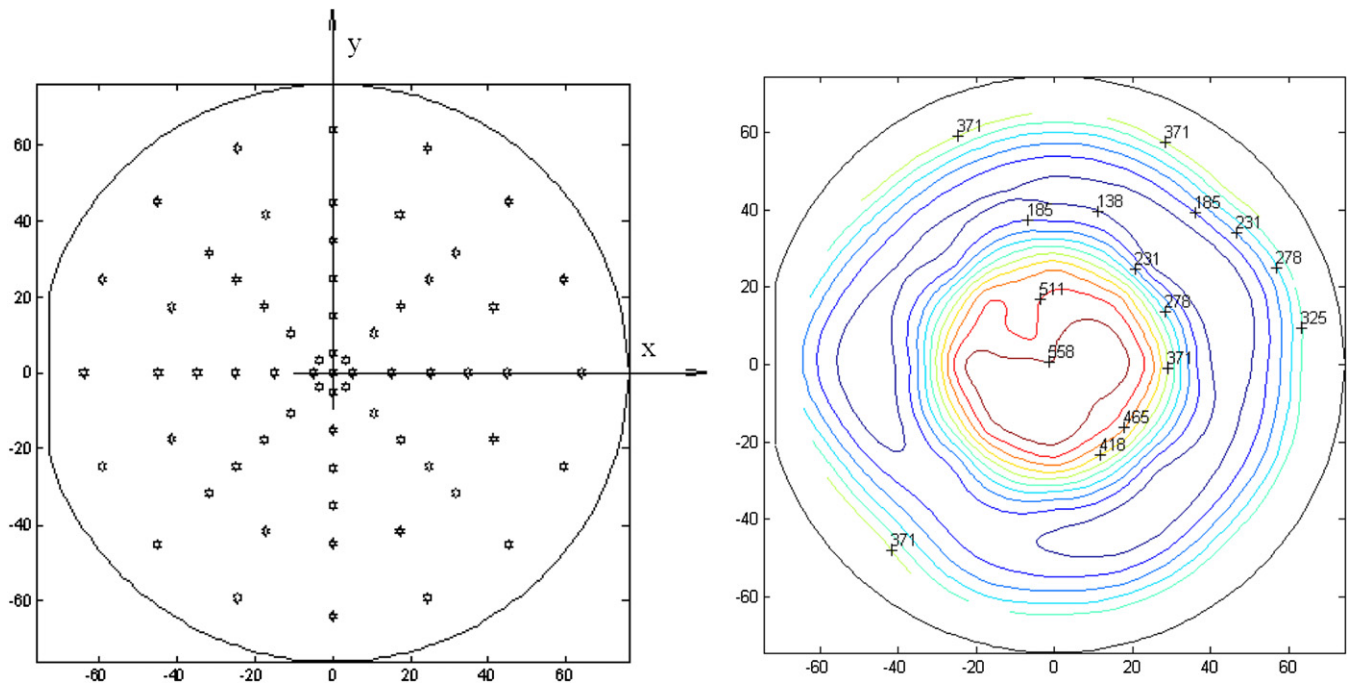


Figure 5. Measurement points and the system of coordinates on the 6 inch silicon wafer. The X -axis (from left to right) is perpendicular to the base cut. Interpolated resistivity values for the high resistivity Si sample numbered HR-Si2. Numbers (resistivity in Ω m) denote contours with constant resistivity values.

Principles of operation of the modern RF eddy current measurement head are shown in figure 8. The eddy current measurement system measures sheet conductance (which is the inverse of the sheet resistance) as a proportional dc voltage. In the high range, the voltage signal is approximately ten times the sheet conductance. The system measures the dc voltage prior to moving the sample under the coil and after the sample is moved under the coil. The system is calibrated using the National Institute of Standards and Technology (NIST) traceable standard reference material. The diameter of the active area of the RF measurement head sample is about 14 mm and the gap size between the upper and the lower head is about 0.9 mm. Practical ranges of the sheet resistance and resistivity for Lehighton instruments are limited by the availability of standard reference samples to $0.1 \Omega/\text{square} < R_s < 10 \text{ k}\Omega/\text{square}$ for the sheet resistance and to $10^{-3} \Omega \text{ cm} < \rho < 10^3 \Omega \text{ cm}$ for resistivity. Relative measurements are possible at broader sheet resistance/resistivity ranges that are only limited by the minimum signal to the noise level. In practice, the upper sheet resistance limit is about $100 \text{ k}\Omega/\text{square}$.

5. Comparison of microwave and RF resistivity and sheet resistance measurements

Comparison measurements of several high resistivity semiconductor samples have been performed at Warsaw University of Technology employing the split-post dielectric-resonator technique (4.8 GHz SPDR) and also at Lehighton Inc. employing the eddy current technique (LEI1510 mapping system). Additionally, the samples have been measured

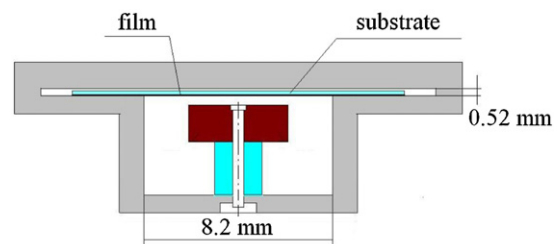


Figure 6. Single-post dielectric resonator (13.3 GHz) intended for measurements of thin conducting films deposited on semi-insulating substrates.

using a four-point probe method. Figure 9 shows the sheet resistance values measured at the center of the wafer by the SPDR method, eddy current technique and four-point probe method. Samples 1, 2, 3, 4 and 6 are high resistivity silicon wafers (TOPSIL), and sample 5 is a GaN stack of roughly $3 \mu\text{m}$ depth, deposited on a sapphire substrate having a thickness of $445 \mu\text{m}$.

An example of the 28-point mapping done by the eddy current method for the 2 inch wafer sample 6 having the largest sheet resistance value is shown in figure 10.

It is seen that the results obtained with different techniques are very well correlated. There are a few possible reasons for discrepancies between individual samples. Firstly, areas of measurements employing different techniques are different. Secondly, for high resistivity samples the accuracy of measurements for the four-point probe method is relatively poor due to no repeatable contacts between the probes and the samples. Thirdly, for the non-perfect uniform samples, their

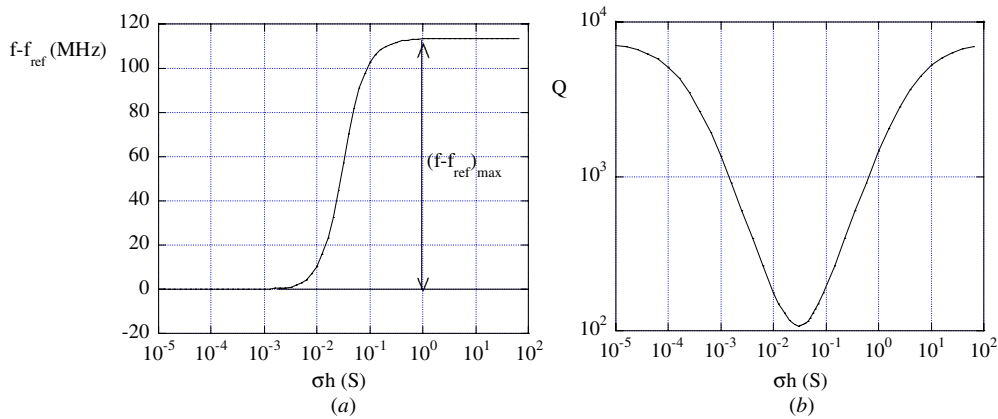


Figure 7. Variations of (a) resonance frequency shifts and (b) Q -factors versus the surface conductivity of thin conducting films for the 13.3 GHz single-post dielectric-resonator.

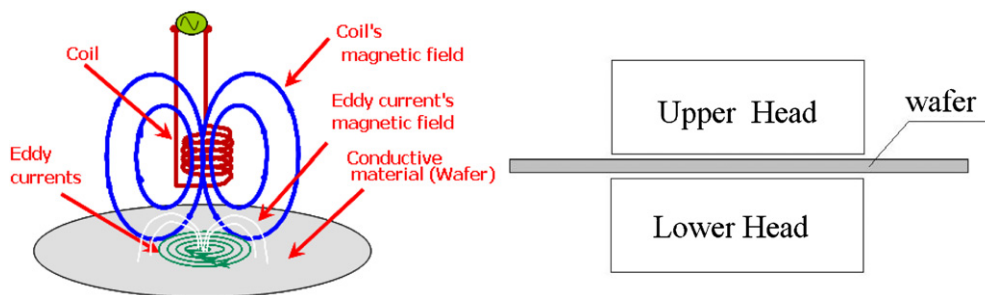


Figure 8. Principles of operation of the RF eddy current measurement technique.

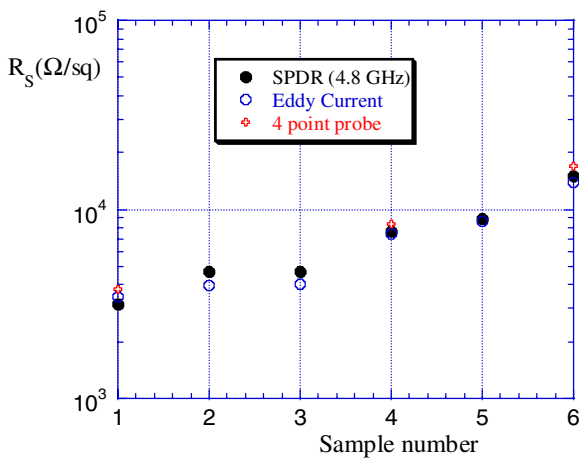


Figure 9. Sheet resistance at the center of a few silicon samples measured with three different techniques. Sample 5 is the epitaxial semiconductor layer deposited on a sapphire substrate.

‘effective’ sheet resistance can be, to some extent, frequency dependent, similar to the metal-dielectric metamaterials so that RF and microwave sheet resistance values can be slightly different. Finally, for samples with large sheet resistance values (>10 k Ω /square), repeatability of RF measurements (based on some initial measurements) is typically of the order of a few percent as is seen in figure 10. Correlation between

different measurement methods is generally better for the samples having smaller sheet resistance values.

6. Summary

It has been shown that both RF and microwave contactless resistivity/sheet resistance measurement methods give similar results within their accuracy and measurement limits. The RF measurement technique is already well established, and mapping instruments are commercially available. Measurements that employ the split-post dielectric-resonator allow measurement of much larger sheet resistance values (especially for thin films) than the RF method but they require additional expensive microwave equipment such as automatic network analyzer to measure the Q -factors and the resonance frequencies of SPDR. Also, microwave methods require reference Q -factor measurements on an empty substrate in order to determine the sheet resistance of thin conducting films that are deposited on the substrate. On the other hand RF methods require calibration of the mapping instrument using standard reference samples while for microwave methods such a procedure is not necessary. The upper limit for resistivity measurements of bulk materials employing microwave techniques is related to the presence of dielectric losses. Technical specifications of RF and microwave resistivity/sheet measurement methods are summarized in table 1.

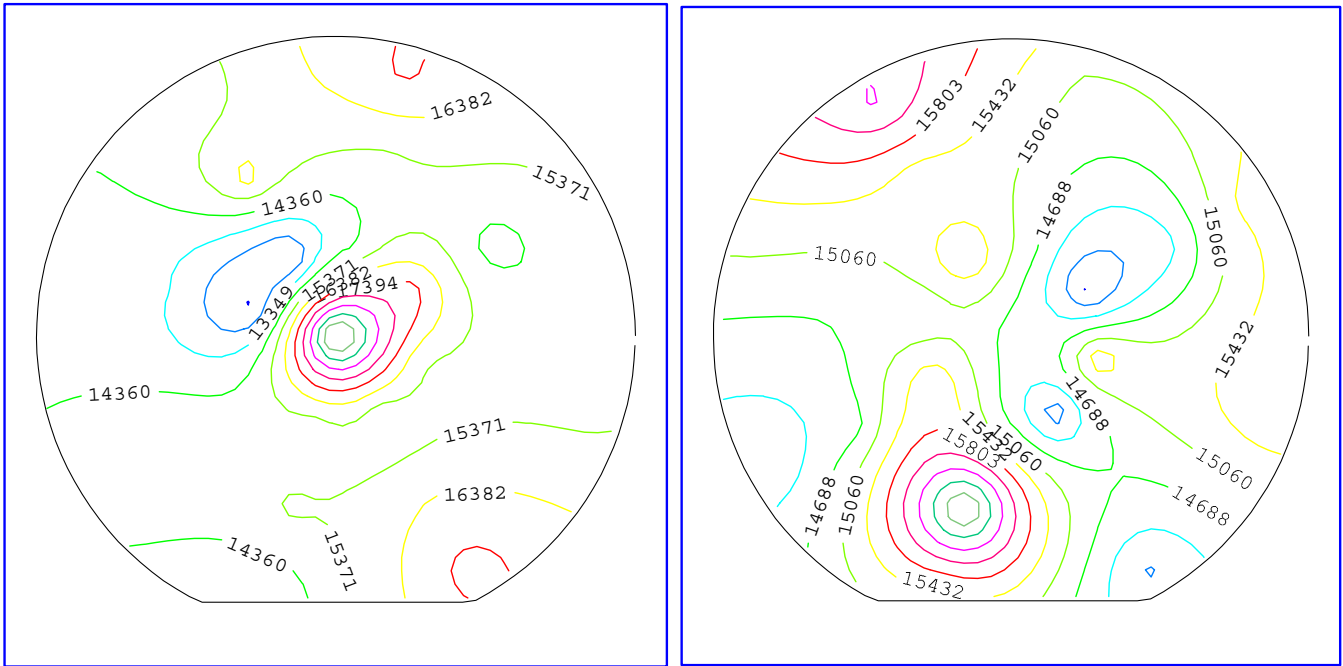


Figure 10. 28-point mapping done by the eddy current method for sample 6 (2 inch wafer).

Table 1. Technical specifications of the RF and microwave resistivity/sheet measurement methods.

Parameter	RF method	SPDR	SiPDR
Min. area/thickness	14 mm/0.9 mm	20 mm/1 mm 10 mm/0.5 mm	20 mm/1.2 mm 8 mm/0.5 mm
Measurement range R_s (Ω)	0.1 Ω –10 k Ω ?	4 k Ω –10 M Ω	0.1 Ω –10 k Ω
Measurement range ρ (Ω cm)	10^{-3} – 10^3 Ω cm	200– 10^5 Ω cm (for $h = 0.5$ mm)	10^{-6} – 10^3 Ω cm
Calibration standards	Necessary	Not necessary	Not necessary
Additional equipment	Not necessary	Necessary (ANA)	Necessary (ANA)
Substrates (for films)	Semi-insulating	Semi-insulating	Semi-insulating or arbitrary for $h > 3\delta$

Acknowledgments

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