

CONTACTLESS DIAGNOSTICS OF THIN FILM LAYERS

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Abstract – Thin layer resistance measurement using the change of complex coil impedance is a contact-less method for conductive layer diagnostics. The analysed sample is inserted into the leakage field of the coil. Our conclusions of a theoretic analysis have been verified in experimental arrangement with a measuring coil and a vector impedance meter. The layer sheet resistance is evaluated by electronic system. A special algorithm, ensuring the explicit evaluation of the measuring, is used for determination of the layer sheet resistance.

Keywords: thin film diagnostics

1. SENSOR PRINCIPLE

An evaluation of complex impedance changes of a coil is a basic principle of this method. A watched sample of a thin conductive layer is inserted into a scattered field of a magnetic coil. This scattered magnetic field generates the induced currents in a sample. Absolute value and phase of induced currents are determined by a sheet resistivity of the sample. Retroactively, induced currents affect the coil impedance due to the magnetic coupling between sample and coil.

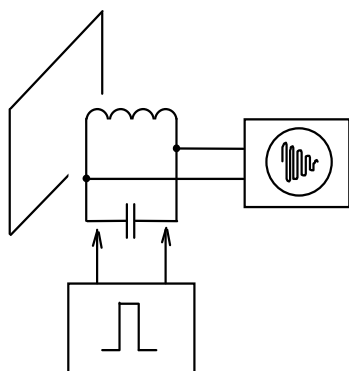


Fig. 1 Measuring principle

Methodology, which was previously in common use, evaluated impedance changes of the coil according to the changes of its quality factor, which was most often evaluated by use of a method of transient-decay oscillation damping of a resonant circuit, which has been created by a measuring coil and capacitor (see Fig. 1).

This method is suitable for not too large range of measured sheet resistance, under certain circumstances. A disadvantage can be in an ambiguousness of the determination of the layer sheet resistance according to a Q-factor change (a change ΔR of a real part of the impedance) of the measuring coil (Fig. 2.).

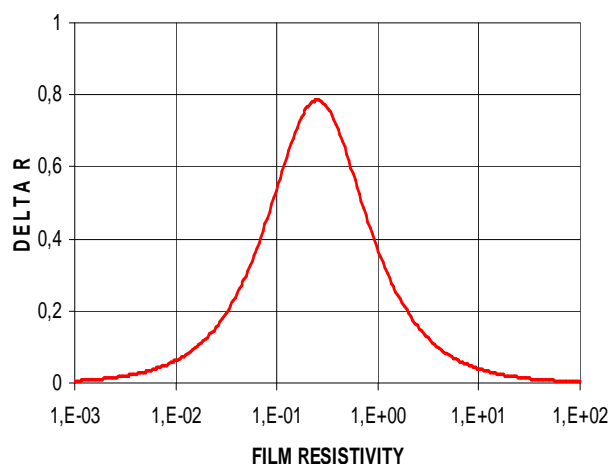


Fig. 2 Damping resistivity

2. ANALYSIS OF MEASURING CIRCUIT

The impedance evaluation of the measuring coil can be explained using schematics of the circuit in fig 3. [1]

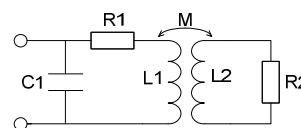


Fig. 3 Measuring circuit

Inductance L_1 , resistance R_1 and capacitance C_1 are parameters belonging to the measuring coil. L_2 and R_2 are inductance and resistance of the measured sample, M is the mutual inductance between the sample and the coil: $M = \chi \sqrt{L_1 L_2}$, where χ is the coupling coefficient.

Parameters L_t and R_t are used in further explanation and represent the influence of the sample to the coil. The resulting circuit is depicted in fig 4.

L_t and R_t can be achieved as follows:

$$R_t = R_2 \frac{\omega^2 M^2}{R_2^2 + \omega^2 L_2^2} \quad (1)$$

$$L_t = -M \frac{R_2^2 + \omega^2 (L_2^2 + L_2 M)}{R_2^2 + \omega^2 L_2^2} \quad (2)$$

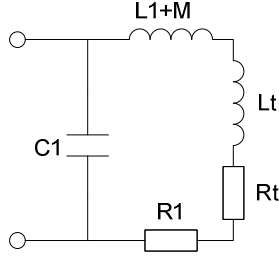


Fig. 4 Equivalent parameters of the measuring circuit

The non-unique determination of the layer resistance R_2 is clearly visible from equation 1. By finding out the measuring circuit quality factor change, the R_t value can be determined. R_2 needs to be calculated by solving the quadratic equation (3). The solution (4) exists only for $R_t \leq \omega M^2 / 2L_2$ and is unique, when $R_t = \omega_d M^2 / 2L_2$ (double root (3)). The solution at ω_d is much easier and unique.

$$R_2^2 - R_2 \frac{\omega^2 M^2}{R_t} + \omega^2 L_2^2 = 0 \quad (3)$$

$$R_2 = \frac{\omega^2 M^2}{2R_t} \pm \sqrt{\left(\frac{\omega^2 M^2}{2R_t}\right)^2 - \omega^2 L_2^2} \quad (4)$$

The resistance of the sample is proportional to this frequency and the inductance of the sample is the proportionality constant.

The solution is unique at the maximum of the following function: $R_t = f(R_2)$. Different R_2 values correspond to different frequencies. If we measure at frequency ω_d , where the function $R_t = f(R_2)$ has its maximum, the R_2 value is unique and proportional to measuring frequency ω_d (5).

$$R_2 = \omega_d L_2 \quad (5)$$

$$\frac{R_t}{\omega} = R_2 \frac{\omega M^2}{R_2^2 + \omega^2 L_2^2} \quad (6)$$

The frequency ω_d can be found as a frequency, where R_t/ω (6) has its maximum. By derivation of equation (6) the condition $\omega_e = R_2/L_2$ arises. Should the extreme be found the other way, then the corresponding equation $R_2 = \omega_e L_2$ allows direct determination of the R_2 .

When we fill $\omega_e = R_2/L_2$ into equation (6), then we get the maximum of the R_t/ω function and as $R_t/\omega = M^2/2L_2$, we gain the equation that corresponds the condition of multiple root (3).

The maximum of the R_t/ω function is kept constant even for different R_2 values (see fig. 5) and therefore the

evaluation does not need to be carried out within a frequency range.

The gained value of ω_e (and consequently R_2) does not depend on mutual inductance M . Theoretically, the obtained R_2 does not depend on the exact position of the sample in the surrounding of measuring coil. However, the misalignment can cause faulty evaluation of ω_e due to inaccurate R_t/ω measurement, when R_t is small.

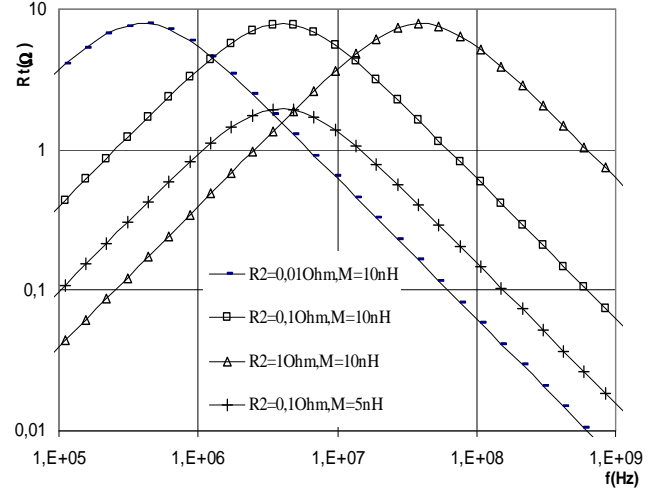


Fig. 5 The R_t/ω curve

3. PRACTICAL PROCEDURE FOR THIN FILM RESISTANCE MEASUREMENT

Our conclusions of a theoretic analysis have been verified in experimental arrangement with a measuring coil and a vector impedance meter. The used measuring coil has 5 windings at the diameter 30 mm, the winding is placed in one layer, whereas the wire diameter is 1 mm. The coil inductance is 1,1 μ H, Q-factor approximately 300 in the range 2-80 MHz, self-resonance is 110 MHz. As samples of thin metal layers the PET foils were used with the Al overlay, with the sheet resistivity from 0,15 to 2,85 Ω /sq and with minimum dimensions of 150x150 mm. During the measurements, a winding axis of the coil was placed vertically to the sample plane, approximately above its centre. The space between the edge of the coil and the sample was set to range from 5 to 60 mm (1/6 up to 2 D).

The $R_t(f) \cdot (f_0/f)$ curves are shown in fig. 6 to 9.

The frequency corresponding to the maximum can be recalculated to the resistance of the thin film (by the use of constant of $43,2 \cdot 10^{-9} \Omega$ s).

The most important quality of described measuring method is further noticeable from presented courses.

Frequency, on which a function peak $R_t(f) \cdot (f_0/f)$ lies, depends only on sheet resistance of measuring film and it does not depend on a coupling of the sample with a measuring coil. Therefore the evaluation according to frequency eliminates major absence of original methodology resistance layers measurement according to quality factor of a coil in resonant circuit [1] that is based only on undesirable dependence of this method on the level of

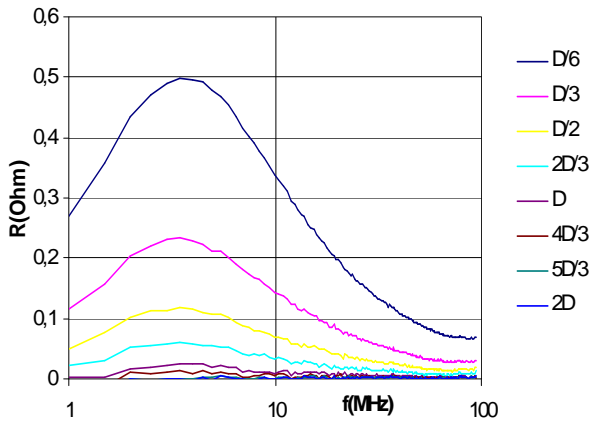


Fig. 6 The layer sheet resistance 0,15 Ω /sq
Vertical samples set up in graph legend corresponds to the vertical position of curves in graph.

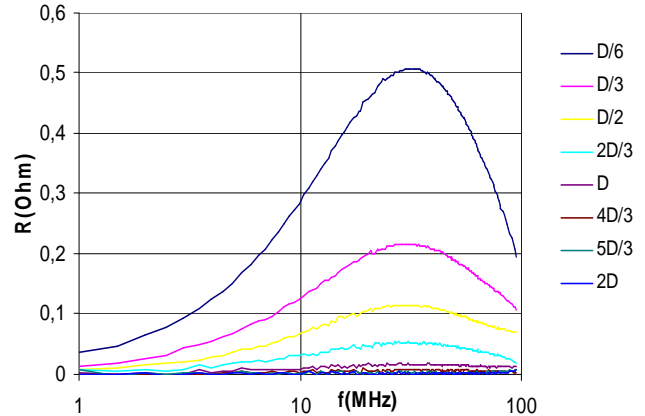


Fig. 8 The layer sheet resistance 1,43 Ω /sq

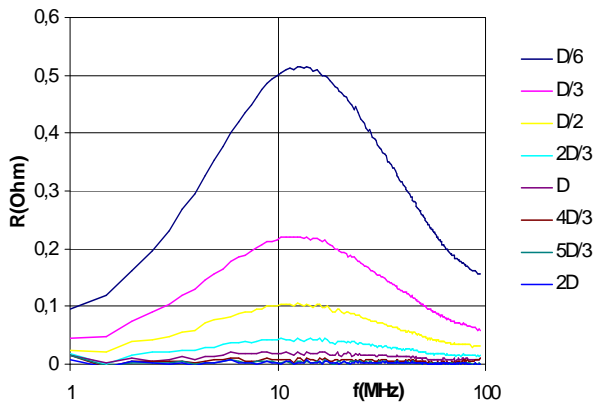


Fig. 7 The layer sheet resistance 0,57 Ω /sq

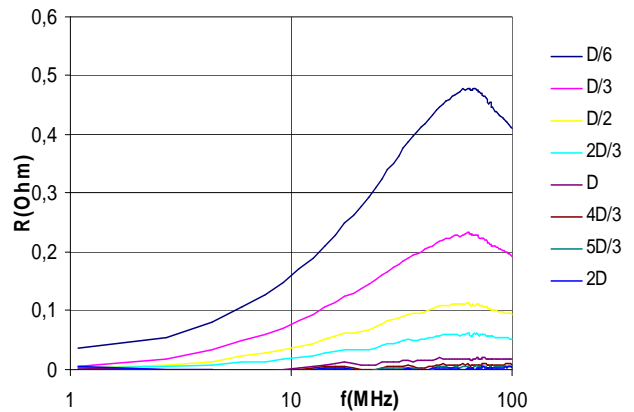


Fig. 9 The layer sheet resistance 2,85 Ω /sq

magnetic bindings of measured conductive layer and measuring coil.

The peak value of the function $R_t(f) \cdot (f_0/f)$ does not depend on a sheet resistance of measuring film in broad measuring range of values and frequencies. It depends only on mutual inductance of measuring coil and a sample of measuring film in case of constant inductance of measuring coil. That is, it depends on the sample dimension and its position against the coil for one measuring coil.

A special digital to analog equipment was used for an automatic evaluation of the frequency dependence of the impedance of the measuring coil and the evaluation of the sheet resistivity of the thin layer. [2]

4. EQUIPMENT FOR THIN FILM RESISTANCE MEASURING

Block diagram of the equipment for the resistance measuring of conductive layers is displayed in figure. 10. Loss resistance of the measuring coil is evaluated in comparative measuring circuit, which consists of measuring coil, (a sample is inserted in its magnetic field,) referential coil, excitation transformer and measuring transformer. The

measuring circuit is supplied by a harmonic current source with variable level and frequency.

The current is constant from the point of view of the loading, created by the measuring coil and referential coil, and it is indirectly proportional of frequency from the point of view of the frequency of exciting signal. An exciting signal with a variable frequency is generated by a wobbler generator, whose frequency is controlled by generator driving signal in selected bounds, e.g. sawtooth generator.

The current is supplied into the measuring circuit from the output of the controlled amplifier, which is excited from the wobbler generator. The output circuit of the controlled amplifier is separated from a measuring circuit by the transformer. The value of the current in a measuring circuit is scanned by a measuring transformer. A sample of this current is led into the amplitude detector through the frequency dependent element with a transmission characteristic, where the transfer magnitude is comparable to the frequency.

Output voltage of the amplitude detector is compared in the differential amplifier with the reference voltage from the source of a reference voltage. The controlled amplifier is controlled by the output voltage of the differential amplifier

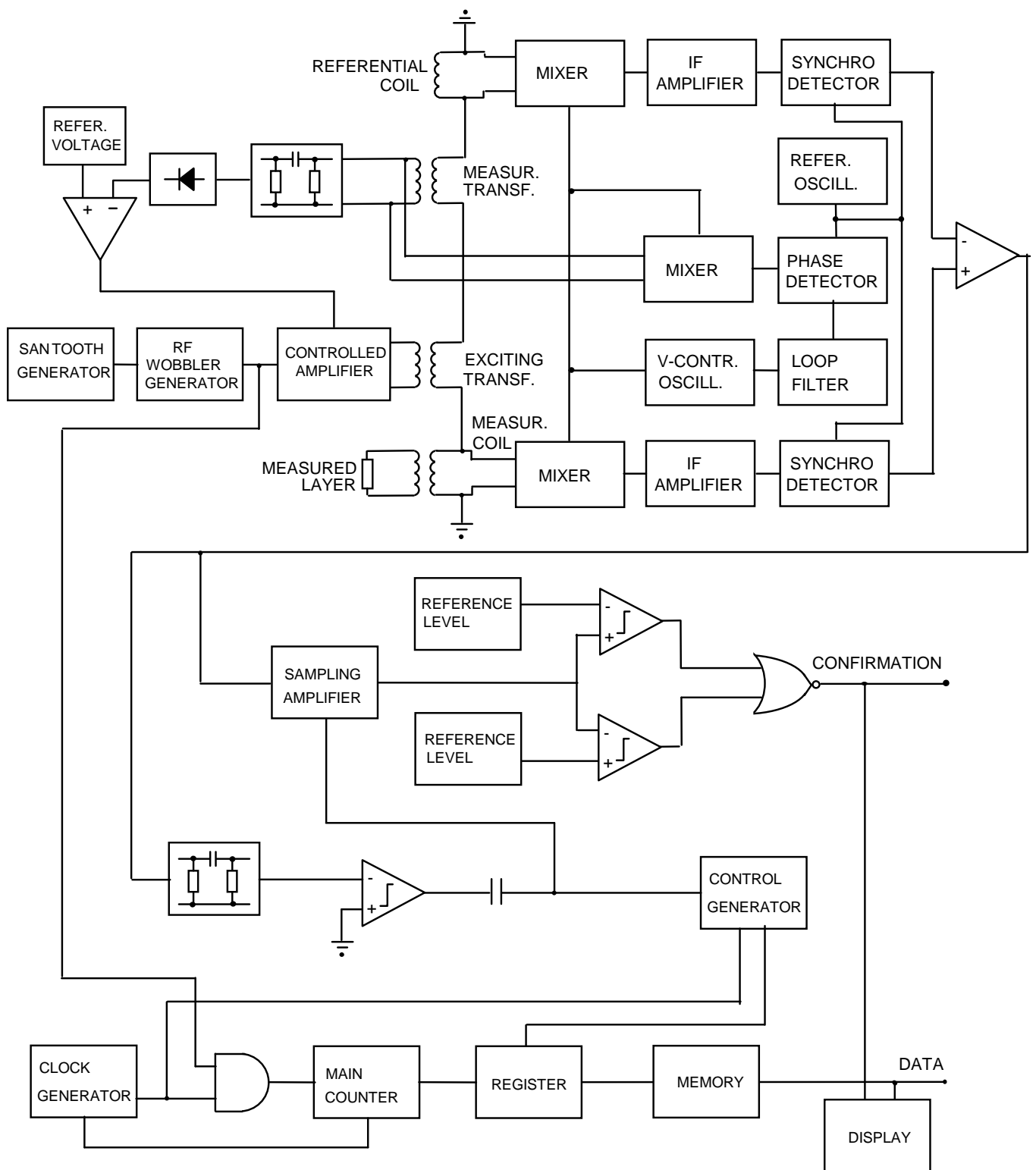


Fig. 10 Block diagram of the measuring equipment

and its gain is set in order that the voltage on the output of the amplitude detector answers to the reference voltage.

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The voltage drop of the measuring coil and the reference coil is a measure of the impedance at themselves. A real part of the coils impedance represents a losing resistance of coils and it matches to the component of the voltage drop, which is in a phase with the exciting current.

An impedance increase of the measuring coil, due to measured layer, is represented by a voltage difference at the measuring and the referential coil.

The magnitude of these voltages is monitored and evaluated by a circuit with a frequency conversion. The signal of local oscillator is generated by a voltage controlled oscillator that is a part of phase locked loop. The frequency of local oscillator is controlled according to the output signal of measuring transformer in order to create the constant intermediate frequency at the wobbling of the measuring frequency. Output signal of the measuring current transformer is mixed with the signal of controlled oscillator and intermediate frequency signal is compared in phase detector with signal of the referential oscillator, which works on constant frequency according to the intermediate frequency. The output signal of the phase detector is processed by a filter and its output signal controls the voltage controlled oscillator.

The frequency conversion in measuring canals of the voltage on measuring coil and in referential coil is implemented by the same two convertors, which use the signal of voltage controlled oscillator as a local oscillator signal. The output intermediate signals of convertors are amplified by the selective amplifiers, whose pass-band matches the intermediate frequency.

Output signals of intermediate amplifiers are led into synchronous detectors that are controlled by a signal of reference oscillator and phase set so that the voltage indicated by them corresponds to real component of the impedance of measuring coil and exciting coil. The difference signal between signals of phase detectors, which is proportional to the difference of loss resistance of measuring coil and referential coil, is generated by differential amplifier. In addition, this signal is related to the function, which corresponds, during sweep period, to the instantaneous frequency, because the current, passing through referential and measuring coil, is controlled according to the instantaneous frequency.

The output signal of differential amplifier then correspond the function R_t/ω , and $R_t(f) \cdot (f_0/f)$, respectively, and layer resistance is determined according to frequency, on which the peak of these functions lies.

The maximum value of the output signal of differential amplifier during a sweeping period is searched automatically according to the derivation of this signal. The output signal of the differential amplifier is derived in differentiator and its output signal is evaluated by a comparator. The synchronizing impulse is generated in time, when the output signal of differentiator is passing through the zero level, and it corresponds to the peak of the output signal of differential amplifier. Just in time of synchronization pulse, the immediate frequency of sweeping generator is further measured.

Instantaneous frequency of sweeping generator is determined by a counter, which is controlled by a clock generator. The clock generator generates a pulse for counter clearing and pulse of exact length for opening a gate feeding sweeper frequency on counter input, periodically, several hundreds times during a sweeping period.

A pulse, recording final state of the counter into a register, is generated in a control generator according to synchronizing impulse, having finished nearest counting period or directly, if counting was finished and counter has not been set to zero yet.

At suitable selected counting time, the number counted in the counter corresponds to the resistivity of the measured layer, which is expressed in certain units. It is possible to include a block memory, in which a correction table is written, at the output of the register, in case a design is needed, which would achieve higher accuracy of the measurement. The input signal from the output of the register determines addresses in memory, whereon numbers are written, that qualify corrected values of resistivity of a measured layer, which are the output signal of the sensor or they can be displayed.

Measurement validity is controlled according to the fact, whether the function peak $R_t(f) \cdot (f_0/f)$ has been found and according to maximum value of the function course $R_t(f) \cdot (f_0/f)$ during the sweeping period.

A peak according to zero value of function derivative will not be found, if the function has a monotone course during sweeping period. It is in a case, when the sheet resistance of measured layer lies out of measuring range of the system.

The maximum value of the function $R_t(f) \cdot (f_0/f)$ during sweeping period does not depend, as it has been noted above, on a sheet resistance of measured layer. The reached maximum value depends firstly on a level of magnetic bindings between the measuring coil and the layer. If a sample is too far from measuring coil, magnetic coupling is low and the change of the loss resistance of the measuring coil is small. The evaluation of peak position is difficult due to disturbance, noise of measuring equipment, evaluation inaccuracy and it is not very precise. It is better not to execute the evaluation of the measurement in this case. The conditions of measurement shall be modified in this case. Similarly, too high indicated maximum value of the function $R_t(f) \cdot (f_0/f)$ during sweeping period indicates the measurement error, which is usually caused by disturbance of the measured layer homogeneity, strong disturbance or by a wrong function of measuring equipment. Also here it is necessary not to execute this measurement, but it is

necessary to find a cause of this condition. Measurement is therefore interpreted as valid only in case the maximum value of the function $R_t(f) \cdot (f_0/f)$ lies in a given range.

The maximum value measurement is evaluated by a sampling circuit and comparators. The output voltage of differential amplifier is led into the analog input of a sampling amplifier. The sampling and recording into the analog memory of the sampling amplifier is synchronized by a synchronizing impulse that is led into the sampling amplifier from the output of comparator. In this way the values of the output signal of differential amplifier, corresponding to the maximum value of this signal, are recorded into analog memory of the sampling amplifier. Output signal of the sampling amplifier is led to signal inputs of two comparators. Referential signals from the generators of reference levels, which correspond to chosen limit values of the function peak $R_t(f) \cdot (f_0/f)$, are led to referential inputs of these comparators. The output signals of comparators are led in a NOR gate, where they are evaluated, so that the true output signal of the gate, which indicates measurement validity, is generated at that when the level of the output signal of sampling amplifier lies between reference levels of generators of reference levels. The output signal of the NOR gate is led to the activation input of the display and displays its input data.

5. CONCLUSIONS

The above stated procedure allows unique evaluation of the layer sheet resistance in the scope of one or two orders, using one measuring circuit and identical physical configuration of the sample, as stated. The samples were measured by above mentioned method and also by four point probe method [3], [4]. The measuring head ER601 was

manufactured by the company Polovodice a.s.. This measuring head contains four in-line placed wolfram pins (electrolytic sharpened, distance 1,06 mm). The value deviation was below 3 % in resistance range from 0,15 Ω/sq to 3 Ω/sq . This can be caused by either inaccuracy of measurement or by lack of uniformity within the vapour deposited layer. Independence on coupling between the measuring coil and the sample, let us say, sample spacing from the measuring coil (approximately in the range 0,1 to 0,6 of the coil diameter), is contribution of the measurement method. This state is especially advantageous within industry for use of this method in the area of an operational monitoring and thin layers diagnostics.

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