Application of an eddy-current method to measure electrical conductivity of thin films

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Abstract. The research objective was the development of subminiature eddy-current transducer (ECT) designed for studying thin films. The possibility of studying the electrical conductivity of thin films of metals as per the amplitude of the eddy-current transducer signal. A subminiature surface eddy-current transducer of the transformer type was developed, and the optimum shape and size of the core and number of inductance coils and turns in them were defined, this provides efficient localization of electromagnetic field. On the basis of eddy-current transducer, a software and hardware complex was developed to control the eddy-current transducer (to generate alternating current of various frequencies, to provide its supply to the eddy-current transducer, to receive a useful signal from transducers to ensure its convenient visualization). The signal working frequency on the energizing winding of the eddy-current transducer was 3 MHz, the signal working amplitude on the energizing winding was 1.1 V. The hardware and software signal processing made it possible to significantly improve the accuracy of measurements. In the developed system, the parameter with information about the monitoring object is the averaged amplitude of the voltage applied by the eddy currents into the measuring winding of the ECT. The algorithm to determine the averaged signal amplitude is given. The dependence between the averaged amplitude of the eddy-current transducer signal and the electrical conductivity of thin films was analyzed and studied. The results of testing of Al, Cu and Zn films were presented, and the electrical conductivity values of the samples were obtained.

1. Introduction

The scientific and technical direction associated with the obtainment and use of thin metal films has remarkably developed over the past decades and occupied key positions in many branches of modern production. At present, the use of thin films in microelectronics, microwave equipment, optics and many other branches of science and technology opens the prospects for the creation and improvement of not only new devices but also entire technological areas. Thin-film conducting structures based on various special conductive films and coatings are used in the electronics industry for the production of integrated circuits, in aviation and space technology, as well as reflective and antireflective coatings in optics and microwave technology.

The variety of structures and specific properties associated with small thickness of such objects leads to the fact that their physical characteristics can differ significantly from the same materials but in the bulk condition.
For the full use of thin films in various areas of electronics, complete information about their material constants and physical parameters, in particular, electrical conductivity, is necessary. Consequently, new methods are needed to determine the characteristics of the materials being studied in the form of thin films.

The various existing methods in the field of resistometry based, as a rule, on creating a good electrical contact between the film surface and measuring elements (electrodes, probes, etc.) can often not be acceptable, since their use can change the properties of the film.

The most significant effect on the quality of the produced conductive films and coatings is provided by reliable monitoring of such important parameters as structural defects, pores, electrical conductivity, thickness, etc. In this case, in view of the considerable technological dispersion of these parameters, it is necessary to carry out 100% outgoing inspection. To monitor these parameters, the following non-destructive testing methods are widely used: visual-optical, capillary, magnetic, ultrasonic, eddy current.

The analysis of works [1-4] showed that eddy current method (ECM) is the simplest, environmentally friendly, and at the same time efficient and high-performance at 100% continuous automatic non-destructive testing of thin films. It is based on the analysis of the interaction of an external electromagnetic field with the electromagnetic field of eddy currents induced by an energizing coil in an electrically conductive film.

From the general considerations developed in work [5], it follows that the efficient technical implementation of the eddy current method of controlling the parameters of thin metallic films is feasible with the help of attachable and screen-type ECTs. It is necessary to develop methods for reliable and accurate control of such parameters of thin non-ferromagnetic films as thickness, specific electric conductivity, the presence of imperfections and structural defects.

The choice of the eddy current method is due to the fact that it has significant advantages in comparison with other methods. It provides the ability to make measurements easily and accurately without the direct contact with the object under investigation, and also provides to make measurements directly in a vacuum, and this allows to more precisely control the process of films growth. In addition, the method makes it possible to carry out a lot of measurements of a wide range of thicknesses of thin films, because of the possibility of a quick change in the penetration depth of eddy currents depending on frequency. [6, 7]

In works [8-13], an eddy current method based on a single-frequency signal was used to study thin films. The use of a single frequency makes it possible to simplify the design of the instrument, but does not make it possible to study thin films at different depths simultaneously. To eliminate this problem, a multifrequency signal is used to control thin films [14-15].

Among a number of models of eddy current defectoscopes currently available on the market, only one-of-a-kind models are good for obtaining thin films. This is due to the thickness of these objects (100-500 nm), which determines a number of requirements to ECT and other components of the system. In particular, the operating frequency range required for studying thin films is 1-10 MHz.

The company Suragus GmbH produces eddy current devices for various purposes, including those designed for the study of thin films. For example, EddyCus® TF lab 2020 allows point-by-point measurements of the electrical conductivity of samples with dimensions from 10×10 mm to 200×200 mm in the resistance range from 0.001 to 3000 Ohm/m² [16].

A significant drawback of this class of instruments is the use of eddy current transducers with a measuring winding radius of 5 to 25 mm, which does not allow achieving high resolution.

An eddy current system is known for studying thin non-ferromagnetic films using the method of resonant screen eddy current nondestructive testing. This system has a high efficiency in detecting defects of thin non-ferromagnetic films of 0.01 μm thickness at the frequency of the excitation current in the range of 10-30 MHz. The disadvantage of this system is the screen-type ECT and as a result the object under investigation should be located in the gap between the measuring and compensation coils, which leads to a significant complication of the design. This is due to the fact that the objects under control can have a base layer of different thickness, so that it is necessary to vary the width of the gap.
between the measuring and compensation coils during the studies. The purpose of this work was the use of an eddy current method to measure the electrical conductivity of thin metal films using a developed measuring system based on a subminiature eddy current transducer that effectively localizes the electromagnetic field in small areas, with subsequent hardware and software processing that allows to process mathematically the received signal.

2. Materials and methods
As the analysis of work [4] has shown, to control the defects of sheets, foils, thin metal films, it is efficiently to use transformer-type attachable ECTs. Based on the results obtained in other works, for example, in [17-18], several designs of a transformer-type attachable ECTs, differing in shape of the core, location of windings, etc., were developed. All ECTs had energizing, measuring and compensating windings.

The energizing and measuring windings contained 200 turns. To wind the turns, copper wire having a thickness of 5 μm was used. The compensating winding contained 140÷170 turns. The cores were made of ferrite 2,000 Nm3 with an initial magnetic permeability value of 500.

The core was a truncated cone with a height of 4.3 mm with a base diameter of 1.5 mm (Figure 1).

![Figure 1. Scheme of ECT windings, 1 — measuring winding, 2 — generator winding, 3 — compensating winding.](image_url)

The measuring winding 1 was located on the tip of the cone (200 turns), the generator winding 2 was centrally located (200 turns) and wound so that the radius was as small as possible to achieve maximum localization of the field.

To eliminate the influence of the generator winding on the measuring winding, a compensating winding 3 was added to ECT. The windings were made of copper wire with a diameter of 15 μm. Windings 1 and 3 were connected according to differential circuit.

The measuring system, which is based on a miniature eddy-current transducer, operates as follows. The software of the personal computer controls the operation of the generator, which produces a train of rectangular voltage pulses with the repetition rate that is necessary for the operation of the eddy-current transducers. The voltage pulses are transmitted from the generator output to two series integrators. They are then directed to the input of the power amplifier. From the amplifier output the voltage pulses arrive at the exciting inductance coils of the eddy-current transducers. The difference of the output voltages of the measuring coils of the transducers contains information on the structural heterogeneities of the tested object that is located in the effective area of the eddy-current transducers.

It is detected and amplified in a special microphone amplifier. The signal arrives at the amplitude detector after the transmission through two series high-quality low frequency filters and two series selective amplifiers. The signal is then transmitted through an analog-to-digital converter to a personal computer. Due to the simultaneous control of the generated signal frequency at the exciting coil and
the cutoff frequency of the filtering system and the selective amplification, the useful signal, which contains information on the electric conductivity distribution inside the object is detected. Special software written in the C++ language for the Windows operating system allows controlling the signal on the exciting coil and receiving the signal from the measuring winding. By means of a special mixer, voltage is applied to the exciting winding of the transducer and the level and frequency of the sinusoidal signal of the generator are set.

Figure 2 shows the relative position of ECT and the object under control. The transducer is perpendicular to the plane OK, so that the measuring winding is at a minimum distance from the OK, but the ETP does not contact the OK.

3. The result and discussion
As objects for studying the operation of the developed system, thin films of metals Al, Cu and Zn, obtained by condensation during the gas phase in a vacuum onto glass substrates, were chosen. The dimensions of the substrates were 23×23 mm. Dimensions of films under investigation were 23×21 mm.

After testing the operation of the system with different amplitudes of the exciting signal and at different frequencies, the amplitude was 1.1 V and the frequency was 3 MHz as the working frequency.

In the developed system, the parameter with information about the object under control is the average amplitude of the voltage introduced by the eddy currents into the measuring winding of ECT. The average voltage amplitude was determined as follows: at the initial stage, the maximum and minimum signal values were measured separately. At the next stage, the average maximum and minimum values of the signal were determined. The difference between the average values <A₁> corresponded to twice the average signal amplitude <U₁>.

Figure 3 shows the initial data — the measured values of voltage on the measuring winding of ECT, in the absence and in the presence of an Al film. Area 1 (N = 150-600) corresponds to the signal in the absence of the object under control — the decompensation of ECT. Area 2 (N = 620-1190) corresponds to the signal in the presence of an Al film. Figure 4 shows the results of using the algorithm for finding the average amplitude.
Figure 3. Voltage on the measuring winding of ECT (Al film). 1 — signal without object of control, 2 — signal in the presence of the film under study.

Figure 4. Determination of the averaged signal amplitude, $<A_1>$ — the signal span without the object of control, $<A_2>$ — in the presence of the Al film on the glass base surface.

In area 1, the average signal amplitude was 14.53 mV, in the area 2-5.41 mV. The difference between the amplitude in area 1 and the amplitude in area 2 ($\Delta <U>$) is 9.12 mV. $\Delta <U>$ for the Zn film was 6.34 mV and for the Cu film was 37.5 mV. Figures 5(a,b) show the results of measuring the response from Zn and Cu films, respectively.

Figure 5. Voltage on the measuring winding of ECT: a – Zn film; b – Cu film.

For Al and Zn films, the voltage applied by the eddy currents is less than the decompensation, and consequently in Figure 3 and Figure 5.a we see a decrease in the signal amplitude. For a Cu film, the contribution of eddy currents is much greater than the decompensation, as a result of which we see an increase in the signal amplitude in Figure 5.b.

To obtain a connection between the values of the average signal amplitude and the electrical conductivity of the material, samples with known electrical conductivity were used.
Based on the results of approximation of the data obtained from measurements of samples with known electrical conductivity, we found the electrical conductivity of Al, Zn, Cu films (Table 1).

Table 1. The results of calculation electrical conductivity of films Zn, Al, Cu.

|   | <ΔU>, mV | σ, MS/m |
|---|----------|---------|
| Zn | 6.34     | 0.1433  |
| Al | 10.89    | 0.5114  |
| Cu | 18.27    | 1.1084  |

4. Conclusion
Eddy current transducer designed to effectively localize an electromagnetic field in small areas of electrically conductive objects has been developed. On the basis of a subminiature eddy current transducer, a measuring system was developed to determine the electrical conductivity of thin non-ferromagnetic films. The measuring system includes: software, hardware, ECT and allows to produce hardware and software processing of the received signal in order to improve the accuracy of measuring the electrical conductivity of thin films. In the course of the work, it was possible to create an algorithm to find the change in the average amplitude of the output signal, the magnitude of which makes it possible to infer the parameters of the film, in particular the electrical conductivity. The samples of thin films were examined using the developed measuring system, the electrical conductivity values of Al, Cu, and Zn films were obtained. For an aluminum film, the electrical conductivity value was 0.5114 MS/m, for a copper film — 1.1084 MS/m, for a zinc film — 0.1433 MS/m. The inaccuracy of the obtained values did not exceed 5%.

References
[1] Yurkov V, Ryzhii V 2008 Effect of Coulomb scattering on graphene conductivity JETP Lett vol. 88, 5 370-373
[2] Abramchuk S 2007 Novel highly elastic magnetic materials for dampers and seals: Part I. Preparation and characterization of the elastic materials. Polym. Adv. Technol vol. 18, 11 883-890
[3] Li W A 2017 Thickness Measurement System for Metal Films Based on Eddy-Current Method With Phase Detection. IEEE Transactions on Industrial Electronics vol. 64, 5 3940-3949.
[4] He D F, Tang J 2017 A contactless method to measure the electrical conductivity, Proc. 3rd “IEEE International Conference on Control Science and Systems Engineering” 305-308.
[5] Bakunov A S, Yefimov A G 2009 Eddy current non-destructive testing in defectoscopy of metal products. Testing. Diagnostics 4 21-22
[6] Angani S, Park D G, Kim G D 2010 Differential pulsed eddy current sensor for the detection of wall thinning in an insulated stainless steel pipe J. Appl. Phys vol. 107, 9
[7] Arez J C 2012 Liftoff insensitive thickness measurement of aluminum plates using harmonic eddy current excitation and a GMR sensor Measurement vol. 45, 9 2246-2253.
[8] Qu Z L 2014 Improvement of sensitivity of eddy current sensors for nano-scale thickness measurement of Cu films. Nondestructive Testing & Evaluation International 61 53-57
[9] Qu Z L, Zhao Q, Meng Y G 2013 In-situ measurement of Cu film thickness during the CMP process by using eddy current method alone Microelectron. Eng 108 66-70.
[10] Li W, Wang H B, Feng Z H 2016 Non-contact online thickness measurement system for metal films based on eddy current sensing with distance tracking technique Rev. Sci. Instrum vol. 87, 4
[11] Kral J, Smid R, Ribeiro A L 2013 The Lift-Off Effect in Eddy Currents on Thickness Modeling and Measurement. IEEE Trans. Instrum Meas vol. 62, 7 2043-3047
[12] Yin W L, Xu K A 2016 Novel Triple-Coil Electromagnetic Sensor for Thickness Measurement Immune to Lift-Off Variations IEEE Trans. Instrum. Meas vol. 65,1 164-169
[13] Wang H B 2015 Noncontact thickness measurement of metal films using eddy-current sensors immune to distance variation *IEEE Trans. Instrum. Meas* vol. 64, 9 2557-2564

[14] Pinotti E., Puppin E. Simple 2014 Lock-In Technique for Thickness Measurement of Metallic Plates *IEEE Trans. Instrum. Meas* vol. 63, 2, 479-484

[15] Yin W, Peyton A J 2007 Thickness measurement of non-magnetic plates using multi-frequency eddy current sensors *Nondestructive Testing & Evaluation International* vol. 40, 1, 43-48.

[16] Busch M 2015 Measurements of the properties of thin films by non-contact (Dresden, SURAGUS GmbH)

[17] Dmitriev S F, Sagalakov A M, Malikov V N 2017 Flaw inspection of welded joints in titanium alloys by the eddy current method. *Welding International* vol. 31, no. 8 46-49.

[18] Dmitriev S F, Sagalakov A M, Malikov V N 2017 Scanning the Welded Seams of Titanium Alloys by Using Subminiature Eddy Current Transducers *Materials Science Forum* vol. 906 147-152.