Control electrically conductive of thin films by using subminiature eddy current transducers

A Ishkov\textsuperscript{1}, V Malikov\textsuperscript{2}
\textsuperscript{1}Department of technology of construction materials and repair of machines, Altay State Agricultural University, Barnaul 656049, Russia
\textsuperscript{2}Physical-technical faculties, Altai State University, Barnaul 656049, Russia

Abstract. The research objective was the development of subminiature eddy-current transducer designed for studying thin films. Timeliness is subject to the need to assess and predict safe operation life of products manufactured using thin films. A review of various methods for thin films studying was made, including the eddy-current method, based on an analysis of the interaction of an external electromagnetic field with the electromagnetic field of eddy currents induced by an energizing winding in an electrically conductive film. A subminiature surface eddy-current transducer of the transformer type was developed. 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 hardware and software complex provided the opportunity to make local studies of the electrical conductivity of non-ferromagnetic thin films by the method of eddy currents. In the course of the study it was possible to develop an algorithm for finding changes in the average amplitude of the output signal, which allows to conclude about the electrical conductivity of the thin film. The study of thin film samples using the developed measuring system is conducted. The results of testing of Al, Ag and Ni films were presented, and the electrical conductivity values of the samples were obtained.

1. Introduction

In recent years, thin films have become increasingly useful in micro-and optoelectronics to create LEDs and photodiodes, sensors, radio frequency tags and other devices. Of particular interest are compounds that may have some advantages over standard semiconductors such as the simplicity and cheapness of methods for obtaining structures in mass production, the ability to create flexible and transparent devices, as well as modification of the properties and variation of the band structure of molecules [1]. In recent times, accurate determination of thin metal films properties is of critical importance in such industries as microelectronics, optics, etc. Thin films are widely used to study electrical properties of new materials when forming the contact surfaces; to apply resistive and conductive coatings in industry and during manufacture of elements of integrated circuits in microelectronics; to create optical filters, and reflective and light-conducting coatings of optoelectronics; modern lithographic processes. An important difference between a thin metal film and a similar metal in the normal state is the difference in electrical conductivity. The differences in conductivity may be great. Therefore, it is extremely important to create a gage system that allows to measure the conductivity of a thin metal film.
According to the results of studies [2-7], it is reasonable to measure electrical conductivity of thin films using the eddy current control method. This method provides the use of an eddy current transducer with energizing and measuring windings. Analysis of the electromagnetic field distribution appeared in a thin film by means of an eddy current transducer allows us to make a conclusion on electrical conductivity of the film.

The use of the eddy current method provides the high performance of control, the possibility of checking without direct contact of the ECT and the surface of the thin film to be checked, the simplicity of the ECT design, and the weak dependence of the control results on environmental conditions [9, 10].

In studies [11-15] the eddy current transducer, the magnetic field of which was single-frequency, was used to measure the conductivity of thin films. This solution allows to simplify the design of the device but does not provide the opportunity to explore the film at different depths. A multi-frequency signal is frequently used to solve this problem [16-18].

The requirements for non-contact and highly precise online thickness measurement of metal films has increased rapidly with the development of industrial automation, semiconductor industry, and micromechanical technology. Compared to X-ray reflectivity and opto-acoustic techniques [19], the eddy current technique [20-22] enables increased flexibility, and it can cover the measurement range from tens of nanometers to a number of millimeters. The main techniques for metal thickness measurement with eddy current sensors can be classified as single-frequency eddy current [21], pulsed eddy current (PEC) [20] and multi-frequency eddy current (MEC) [22] sensors based on the types of excitation signals. In the single-frequency eddy current technique, the sensor coil is excited with a sinusoidal signal and the eddy currents are distributed in a fixed depth. It is the most traditional method and is the basis of other methods.

Due to the small thickness of thin films (100-2000 µm), only a few models on the market allow to study their conductivity. In particular, this is due to the range of operating frequencies required for the study of thin films, which is 1-10 MHz.

There is an eddy current system designed for the study of thin metal films, which implements the method of resonance screen eddy current defectoscopy [9]. The system is highly effective in detecting defects of thin non-ferromagnetic films, the thickness of which is 0.01 µm at the frequency of the exciting current in the range of 10-30 MHz. The disadvantage of this system is the screening transducer, where the thin film should be located in the gap between the measuring and compensation coils. This complication of the design is due to the fact that the investigated films can have a substrate of different thickness, and it is necessary to vary the width of the gap between the measuring and compensation coils in the studies.

The aim of the study is to develop a measuring system based on the eddy current transducer designed to measure the conductivity of thin metal films capable of localizing the electromagnetic field in small areas of the object of control.

2. Material choices and design
In accordance with the paper [23, 24], the following design of the eddy current transducer was constructed:

Exciting and measuring coils contain 200 turns. The wire for coils is 5 µm thick. The stabilizing coil contains 140–170 turns. The cores are made of permalloy 81NMA with an initial magnetic permeability of 35000 (Fig. 1).
The design of the eddy current transducer used to test steel pipes was a magnetic core made of permalloy 81NMA in the shape of a pyramid. The energizing winding, measuring winding and compensating winding were wound on the magnetic core. The winding turns were impregnated with epoxy compound to form monolithic structure [25, 26].

The difference between the averaged amplitudes of the signals of the transducer, which is paced above the thin metal film and the transducer paced above the substrates, is the parameter of the film electrical conductivity. The generation unit controls the generator, which transmits a signal of frequency $f_1$ to the energizing windings of eddy current transducers, these ETCs create an electromagnetic field that induces eddy currents in an electrically conductive test object. The signals pass through power amplifier, where their voltage rises up to 3 V that is necessary to carry out the measurements, and pass to energizing windings of eddy current transducers. As a result, the energizing windings create a magnetic field that penetrates the tested thin film and substrate. The magnetic field induces eddy currents in the test sample, which, in turn, induces a voltage in the measuring windings. The voltage in the form of signals $C_1$ and $C_2$ carries information about the substrate and the thin film, respectively. The signals pass through the amplifiere-computer 8 and pass to the signal filtering unit, controlled by the filtering software unit connected with the generation software unit. The filtering frequency changes simultaneously with the generation frequency. Two signals are transmitted to the amplitude detector, through the analog-to-digital transducer, to the signal processing software unit and the measurement results are displayed in a form of a diagram on the PC screen and the difference values of the averaged amplitudes of the two signals $C_1$ and $C_2$ are displayed. Electrical conductivity ($\sigma$, MSm/m) is determined according to the experimentally obtained equation $f(x) = 0.0809x - 0.3696$, according to the diagram of film samples with known electrical conductivity, where point 1 corresponds to the aluminium sample with electrical conductivity of 0.1 MSm/m and a signal amplitude difference is 16.8 mV, point 2 corresponds to a sample of aluminium with a conductivity of 1.23 MSm/m and a signal amplitude difference of 19.6 mV.

3. Experimental results

The studies of the signals of the designed transducer were carried out on samples representing thin films of such metals as Al, Ag, and Ni obtained after condensation during gas phase in vacuum on glass substrates. The dimensions of the substrates are 23 x 23 mm. The investigated films have dimensions of 23 x 21 mm. This method stipulates the use of two signals, where the difference of averaged amplitudes ($<\Delta U>$, mV) of two signals (the signal from zone 1 and the signal from zone 2) is used as a parameter of the film electrical conductivity, and the electrical conductivity of the thin metal film is calculated by experimentally obtained equation $f(x) = 0.0809x - 0.3696$, where $x$ is the difference of the amplitudes $\Delta <U>$ of the two signals $C_1$ and $C_2$. 

![Figure 1. Design of the eddy current transducer, 1 — measuring winding, 2 — generator winding, 3 — compensating winding.](image-url)
Fig. 2 shows the superimposed data obtained during study using two transducers. Zone 2 corresponds to the data obtained using the transducer placed above the film, zone 1-3 — to the data obtained using the transducer placed above the substrate without the film.

**Figure 2.** 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.

In Fig. 3, the results of the algorithm for finding the average amplitude are presented.

**Figure 3.** Determination of the averaged signal amplitude, $\Delta U_1$ — the signal span without the object of control, $\Delta U_2$ — in the presence of the Al film on the glass base surface.

In the area 1 the averaged amplitude of the signal is equal to 29 mV, in the area 2-3 - 10.8 mV. The difference between the EMF amplitude in the area 1 and the EMF amplitude in the area 2 ($\Delta<U>$) is 18.2 mV.

$\Delta<U>$ for Ag film is 8.31 mV and for Ni film-21.35 mV.

In Fig. 4 and Fig. 5 the results of measuring the response of Ag and Ni films, are presented respectively.
Analysing the distribution of the signal in Figures 2, 4, one can notice a drop in the amplitude of the signal received from the transducer placed above the film, compared with the amplitude of the signal placed above the substrate. This feature is explained by the insufficient compensation of the windings of the eddy current transducer, as a result of which the initial magnetic field of the energizing winding, affecting the measuring winding, weakens under the influence of the magnetic field of the eddy currents of the film under study.

However, for the Ni film, the magnetic field of the eddy currents of the film under study is much higher than the magnetic field of the energizing winding (Fig. 3). As a result, the influence of the magnetic field of the energizing winding is completely dropped out of the equation, and only the magnetic field of the eddy currents of the film is of concern.

Based on the data obtained and in accordance with the experimentally obtained equation $f(x) = 0.0809x - 0.3696$ based on samples of films with known electrical conductivity the conclusion on the electrical conductivity of the films under study may be drawn (Table 1).

|          | $<\Delta U>$, mV | $\sigma$, MS/m |
|----------|------------------|----------------|
| Ag       | 8.31             | 0.161          |
| Al       | 18.2             | 0.5114         |
| Ni       | 21.35            | 0.956          |
4. Conclusions
The results of the experiment showed the effectiveness of the proposed method of controlling the electrical conductivity of thin films with electrical conductivity from 0.1 to 1 MSm/m. To achieve this goal, we used developed ultra-miniature eddy current transducers with a filtering system for the received signal.

Using the developed algorithm to determine the electrical conductivity of the film on samples with known electrical conductivity, it becomes possible to draw a conclusion about the electrical conductivity of the material under study.

Further improvement of the developed prototype of the gage system can be carried out both by increasing the efficiency of the applied signal processing algorithms and by upgrading the hardware. In this case, the first steps should be usage of more efficient digital filters and high resolution analog-to-digital transducers.

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