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REVIEW OF METHODS FOR INVESTIGATION OF ELECTRICAL PARAMETERS OF SEMICONDUCTOR MATERIALS

(review-research)

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ABSTRACT

The paper presents a variety of modern trends and prospects for methods for measuring the electrical parameters of a solid body. The demand for the work is due to the fact that the development of research methods can make a further contribution to the progress of alternative energy, contributing to the expansion of the range of semiconductor materials with new properties. General information on bridge and non-contact methods for studying electrical parameters is given. A forecast of the development of microwave and magnetic induction methods for studying the electrical parameters of semiconductor and other promising materials is shown. The significant progress achieved in recent years in the development of these research methods is shown. The work is of interest to researchers involved in the synthesis of new materials for the development of alternative energy.

Keywords: alternative energy. electrical materials. semiconductors, electronic conductivity, conduction channels, magnetic induction research methods.

INTRODUCTION

Due to the sharp increase in the population of the Earth, the demand for energy of various types is sharply increasing. In this regard, there is an acute issue of improving and developing alternative energy sources, which include semiconductor converters of solar radiation energy. Silicon semiconductor materials are mainly used for mass production, but the coefficient of performance (COP) of such devices is in the range of 18 percent. Everywhere in scientific laboratories, the search for new materials is being actively pursued, on the basis of which it is possible to obtain greater efficiency. However, developers often have to face the problems of express analysis and non-destructive testing of various parameters of new materials. Such studies require reinforcement of the instrumental base. One of these most important parameters is resistivity [1].

METHODS

Conductivity can be evaluated by various methods: direct and indirect measurements, contact and non-contact methods. In contact methods, the power source that creates an electric field in the sample, as well as the elements of the measuring circuit, are directly or contact-connected to the sample. These methods include: the single bridge method, the double bridge method, the potentiometric method, the ampere-voltmeter method, as well as the four-probe method [1]. Let's briefly consider these methods. To measure the conductivity of various materials, bridge circuits are often used, carried out using measuring bridges. Such circuits are characterized by the presence of a bridge branch between two points in the circuit that are not directly connected to a source of electrical energy. At their core, bridge circuits are an evolution of the measurement method based on the Wheatstone bridge. Bridge measurements are mainly used to measure resistance and conductivity. Such measurements are the most common and advanced measurement methods.

Single bridge method. This method is applicable when measuring samples with high resistance (> 10 Ω) and provides satisfactory accuracy, since the resistance of the contacts and potential current leads to the sample contribute to the measured value. A schematic diagram of a single bridge is shown in Fig.1.

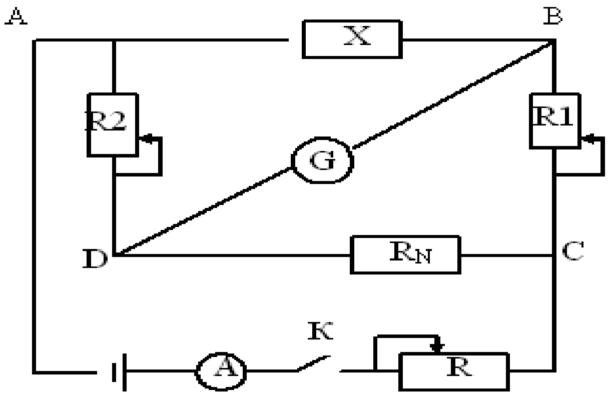


Fig.1. Schematic diagram of a single bridge.

The circuit is based on three known resistances: R_1, R_2 and R_N (reference) and one unknown - X. To determine this resistance, the bridge is balanced by changing the resistances R_1 and R_2 or R_2 / R_1. In this case, the potentials of points B and D are aligned with themselves and the current flowing through the galvanometer G, according to the Kirchhoff law, becomes equal to zero. In this case, we will use the formula for the calculation:

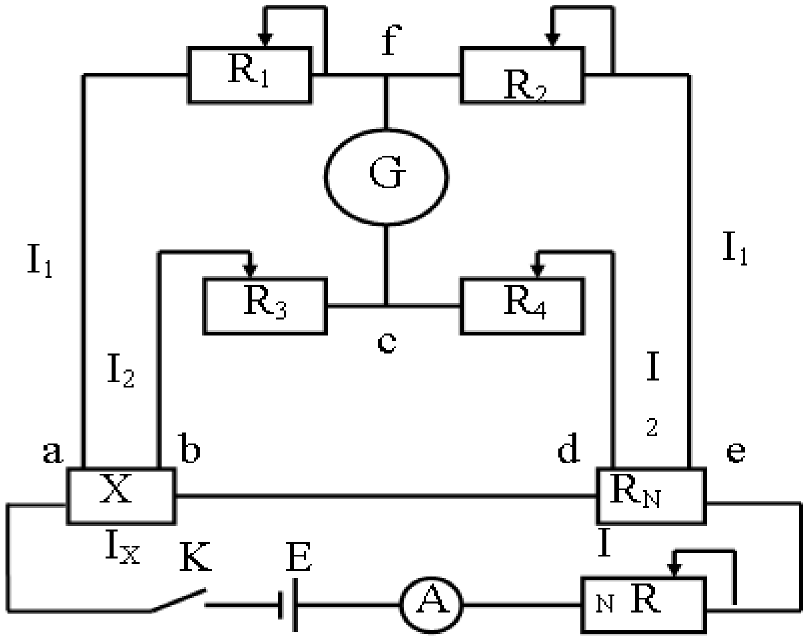
$$X = R_N \frac{R_2}{R_1} \quad (1)$$

Derived according to the bridge equilibrium rule. The balance of the bridge can be achieved by closing and opening one of its diagonals is not accompanied by the appearance of a current in the other diagonal. This method is called the null method or the single bridge method.

The single bridge method can also be used to measure low resistances. At the same time, it is possible to reduce the influence of contacts and potential current leads by alternately switching on an unknown X resistance in different branches of the bridge.

Double Bridge Method

This method is presented in Fig.2. The method makes it possible to measure low resistances with high accuracy (from 1 ·10-6 to 1 Ohm). We turn the circuit into a single bridge, by simply changing the circuit.



Rice. 2. Schematic diagram of a double bridge.

The application of the double bridge method for measuring low resistances or their small changes is based on the fact that the additional resistances of the contacts and potential current leads associated with the sample do not affect the potentials of the points f and c, to which the zero – galvanometer is connected, since the value of the intermediate resistances R_1, R_2, R_3, R_4 are much larger (> 100 Ohms) than the indicated additional resistances.
By varying the resistances $R_1 – R_2$, $R_3 – R_4$ at the reference R_N, the potentials of the points f and c are balanced, achieving a zero reading of the galvanometer. At the moment of equilibrium of the bridge, the voltage drops in the sections af and fe must be equivalent to the voltage drops in the sections ac and ce, respectively. However, the method is also applicable for measuring rather large resistances.
The potentiometric method guarantees stable accuracy when measuring low resistances. In this case, the voltage drop across the sample is compared with the voltage drop across the reference resistor connected in series. The voltage drop ED and EN is measured with a potentiometer. In this case, the working formula for the desired resistance X is:

$$X= R_N(E_X /E_N) \qquad (2)$$

here R_N is the standard resistance; EX and EN are the voltage drops across the unknown resistance and reference, respectively.
Ammeter – voltmeter method. To determine the electrical resistance, it is necessary to measure the current in the circuit using a digital ammeter A, as well as the voltage drop over the length of the measured resistance X using a digital voltmeter V. The measuring circuit of the method is shown in Fig.3.

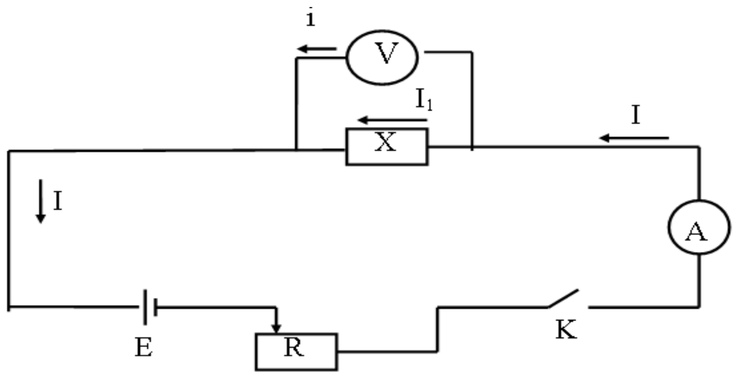


Fig.3. Schematic diagram of measurements using the ammeter-voltmeter method.

The resistance value is determined by the formula $X = \frac{U}{I}$, where U is the voltage drop, V; I-current strength, A. Determination of resistance in this way is not accurate, since the ammeter measures the amount of current I1 flowing through the sample, as well as the amount of current i flowing through the voltmeter. True sample resistance

$$X_t = \frac{U}{I_1 - i} = \frac{U}{I_1 - \frac{U}{r_V}} \quad (3)$$

Where rV is the resistance of the voltmeter windings. The error resulting from the calculation by the formula

$$X = \frac{U}{I} \quad (4)$$

the greater, the lower the resistance of the voltmeter and the greater the resistance of the sample. By increasing the resistance of the voltmeter by more than 100 times compared to the measured resistance, you can use the formula $X = \frac{U}{I}$ and this will give an error of up to 1%. To do this, a large additional resistance should be connected in series with the voltmeter (a method of increasing the measurement limits of the voltmeter). The accuracy of this method will depend mainly on the accuracy of the ammeter and voltmeter used and the magnitude of the transient resistances at the points where the devices are switched on and the resistance being measured. At present, electronic digital electrical meters should be used. By connecting the recorder to a computer, you can continuously record instrument readings.

Classical methods for measuring the resistance of semiconductor crystals are complex and involve the manufacture of ohmic contacts. The creation of ohmic contacts can lead to the formation of additional defects in the crystal structure of the material under study and lead to an increase in the measurement error. Therefore, in modern research, non-contact methods for measuring the resistivity and conductivity of various crystalline substances become the most cost-effective. These methods include the four-probe method or the improved van der Pauw method.

The four-probe method for measuring the resistivity of semiconductors is the most suitable. This is due to the fact that its application does not require the creation of ohmic contacts to the sample; it is possible to measure the resistivity of samples of the most diverse shapes and sizes. A necessary condition for the shape of the sample is the presence of a flat surface with linear dimensions of the measuring probes. On fig. 4. shows the scheme for measuring resistance by the four-probe method.

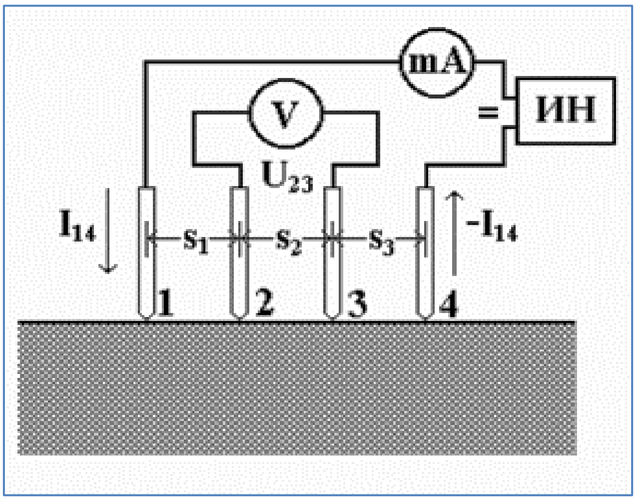


Fig.4. Scheme for measuring resistance by the four-probe method.

Here in the figure the following designations are shown: IN - a source of constant voltage; V - voltmeter; mA is a milliammeter.

Four metal probes with a small contact area are placed along a straight line on the flat surface of the sample. Distances between probes s_1, s_2 and s_3. Electric current I_{14} is passed through external probes 1 and 4, potential difference U_{23} is measured on internal probes 2 and 3. The measured values of I_{14} and U_{23} can be used to determine the resistivity of the semiconductor (shown in gray in the figure).

If the distances between the probes are the same(i.e. $s_1=s_2=s_3=s$):

$$\rho = 2\pi s \frac{U_{23}}{I_{14}} \qquad (5)$$

Thus, to measure the electrical resistivity of a sample by the four-probe method, it suffices to measure the distance between the probes s, the voltage drop U_{23} across the measuring probes, and the current flowing through the sample I_{14}.

In view of the foregoing, the simplest method recommended for measuring the resistivity of semiconductors is the four-probe method, which does not require the creation of ohmic contacts.

Here in the figure the following designations are shown: IN - a source of constant voltage; V - voltmeter; mA is a milliammeter.

In recent years, other non-contact research methods have appeared. Microwave methods belong to the class of so-called non-contact methods, which also include the eddy current method, quasi-optical, optical and electron diffraction methods. Measurements of the parameters of semiconductors at direct current are carried out with direct contact of the probe with a semiconductor sample. Often the use of probe methods is associated with the destruction of the material under study. The injection of charge carriers into the material associated with the contact, the presence of a contact potential difference, and the occurrence of thermal EMF lead to sources of measurement error that are difficult to eliminate and difficult to take into account. The role of these effects and their influence can change significantly depending on the temperature, which makes it difficult to carry out measurements in a wide temperature range. To reduce the influence of the contact, it is desirable that it be non-rectifying "ohmic". Ensuring the "ohmic" contact is a rather difficult task, especially for high-grade materials. It is difficult (or rather, even incorrect from the point of view of the information obtained) to study polycrystalline samples by probe methods, as well as small-area samples with arbitrary geometry. As a rule, one unknown parameter can be determined with the help of probe methods on one installation for the sample under study [3].

All of the listed methods for measuring conductivity require the use of external contacts. When using such methods, one has to put up with the difficulties of determining the true volume resistance of the sample due to polarization effects at the boundaries between the electrolyte and the electrode. The use of non-contact methods makes it possible to get rid of many difficulties.

The meaning of all non-contact methods is reduced to the induction of eddy currents inside the sample in a changing magnetic field. There are two ways to measure the electrical conductivity of solid samples:

1) By placing the sample in a rotating magnetic field.
2) Place the sample in the inductor.

In a rotating magnetic field, the measurement of conductivity is based on measuring the magnitude of the moment of forces acting on the sample. It generates induced eddy currents with different amplitudes, the magnitude of which depends on the electrical conductivity of the sample. The resulting currents interact with the magnetic current, which creates a torque that must be fixed.

Methods involving an inductor are based on a change in its impedance when a sample is introduced into it. The introduced sample interacts with the magnetic field of the coil, as a result of which the complex resistance of the inductor changes, depending on the conductivity of the sample material.

In non-contact methods, the EMF in the sample is created as a result of the phenomenon of induction, which makes it possible to measure the electrical resistance in sealed vessels, at high temperatures, melts, etc. These methods include:

- method of rotating magnetic field;
-method of eddy currents;
- a method based on the reflection of the energy of microwave oscillations.

Let us briefly describe these methods.

Rotating magnetic field method. The electrical conductivity in this case is determined by the magnitude of the moment of forces acting on the sample, measured by the angle of suspension twist. The accuracy of the method is -1%, but to achieve such an accuracy, corrections are introduced for the shape and self-induction of the sample, by monitoring the state of ferromagnets. The rotating magnetic field method can collect a sufficient amount of information not only on electrical parameters. So the method is applicable to determine the viscosity of solutions and many other parameters [4].

Eddy current method. In this method, the sample is placed in an alternating magnetic field of an inductor. Under the influence of this field, eddy currents are excited in the sample, which change the total electrical resistance of the inductor, the change of which characterizes the electrical resistance of the sample.

A method based on the reflection of the energy of microwave oscillations. In this method, used for semiconductors, the electrical resistance is measured by the reflection coefficient of an electromagnetic wave, which depends on their conductivity (the dielectric constant is assumed to be constant).

RESULTS

To find the minimum values for errors in the measurement by various methods described above, we chose the eddy current method with the sample placed in an inductor. The method is simple and accessible. For comparison, we present the calculated and experimental values for silicon and germanium samples.

Table 1. Dependence of the specific conductivity of n-Si on the effective carrier concentration (ND-NA) at 300 K, obtained by the eddy current method with the sample placed in an inductor.

ND-NA, sm^{-3}	s_1, $(Om\ sm)^{-1}$
$2.9 \cdot 10^{19}$	430
$2.4 \cdot 10^{18}$	95
$1.3 \cdot 10^{17}$	70
$1.8 \cdot 10^{16}$	10
$1.9 \cdot 10^{15}$	0.81
$1.6 \cdot 10^{14}$	0.03

Table 2. Resistivity of n-Ge versus effective carrier concentration (ND-NA) at 300 K

ND-NA, $см^{-3}$	s, $(Om\ sm)^{-1}$
10^{13}	180
$9.4 \cdot 10^{13}$	17
$5.1 \cdot 10^{14}$	10
$5.1 \cdot 10^{15}$	0.5
$7.5 \cdot 10^{15}$	0.3
$5.5 \cdot 10^{16}$	0.05
$4.2 \cdot 10^{17}$	0.03

Table 3. Measured and calculated values.

№	T, мВ	T, К	$\frac{1}{T}$, $К^{-1}$	I, A	U, B	$(Ом/м)^{-1}$	*ln*
1	3.9	330	0.0023	0.002	0.03	0.0674	2.70

DISCUSSION

As can be seen from the above results, the eddy current method with the sample placed in an inductor is distinguished by its simplicity and accessibility. The measurements obtained by this method give the values closest to the calculated ones.

Thus, the variety of research methods [5-8] for structures with given parameters is a significant help to developers of various modern technical devices. The greatest simplicity and accessibility among which are non-contact methods.

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