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**Impedance of Si Wires at Metal-Insulator Transition**

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Impedance spectroscopy for Si wires with dopant concentrations near the metal-insulator transition in the low temperature range 4.2 - 70 K and frequencies 0.01 - 250 kHz has been conducted. The studies allow us to obtain parameters of hopping conduction (localization radius, density of localized states and average length of carrier jumping) and compare them with theoretical data.

**Key words:** Si wires, magnetoresistance, impedance spectroscopy, localization radius.

Измерения электрических и магнито-электрических свойств донорных Si проволок интересны как с практической, так и с фундаментальной точки зрения, из-за уникальных и привлекательных свойств (высоких уровней механической прочности и мобильности носителей заряда)

**Introduction**

Investigation of electrical and magnetic properties of doped Si wires is interesting both from a practical and a fundamental point of view, due to the unique and attractive properties (high levels of mechanical strength and mobility of charge carriers)[1-3]. Therefore, the question arises comprehensive study of electric and magnetic properties of the material using modern approaches, including impedance spectroscopy, which allows to deepen knowledge of the magnetoresistance and electrical properties of Si wires, their behavior under various external influences, nature and the relationship of these effects, etc.

On the other hand, because of the possible influence of microstructural features on the charge carrier transport these materials require more detailed consideration and research using both DC and AC measurements[4-6]. Therefore, the study of the frequency change of the electrical properties of Si wires with their real microstructure is an important and urgent task.

In this paper the method of impedance spectroscopy has been considered for Si wires with dopant concentration near the metal-insulator transition (MIT) in the low temperature range 4.2 - 70 K and frequencies 0.01 - 250 kHz. It is shown that the application of the method of impedance spectroscopy gives an additional information about the nature of conductivity in doped Si wires near MIT and possible recharge processes in the system of impurity centers.

I. The experimental results

Silicon wires crystals were grown by chemical transport reaction method in a closed bromide system using boron impurities for doping and gold as initiating growth. Crystals had 10-40 µm in diameter and 0.3-1 cm length. The wires concentration varied from $2 \times 10^{18}$ to $2 \times 10^{19}$ cm$^{-3}$. Contacts to the crystals were created as a method of arc welding platinum microwire with a diameter of 15 µm and a special method of anodizing silver on the surface of wire ends and then installing them on substrates with aluminum tracks. Both methods provide ohmic contact to the samples in the temperature range 4.2 - 300 K. Crystals resistance has been measured by four contacts method. Accuracy of resistance measurement is less than 1%. During the experiments three groups of samples with boron impurity concentration corresponding to $\rho_{300K} = 0.0143$ Ohm$\times$cm, $\rho_{300K} = 0.0155$ Ohm$\times$cm, $\rho_{300K} = 0.0168$ Ohm$\times$cm in the dielectric side of the MIT. Frequency dependence of impedance for Si wires was obtained by measuring device Losk=in in the frequency range 0.01-250 kHz at fixed values of temperature in the range 4.2 - 70 K.

![Fig. 1. Temperature dependence of samples with resistivity $\rho = 0.0168$ Ohm$\times$cm.](image-url)
At the beginning the study was carried out at a constant current in the temperature range 4.2–300 K and in magnetic fields up to 14 T. Temperature and magnetic dependencies obtained at constant current in the temperature range 4.2–300 K for typical samples are shown in Fig. 1–4, correspondingly.

According to Mott law at finite density of states at the Fermi level \( g(E_F) = \text{const} \) equal to 1/4 and the parameter \( T_0 \) is defined by the following expression

\[
T_0 = \frac{17.6}{g(E_F) a^3 k_B}
\]

where \( a \) is the radius of localization of the wave function. This component of the magnetoresistance due to compression of the wave function in magnetic field is determined by following equation

\[
\ln \left( \frac{\rho(H)}{\rho(0)} \right) = \frac{5}{2016} a^4 H^2 (T_0 / T)^{1/4} / (c^2 \hbar^2)
\]

As follows from the equations (1-3), simultaneous measurement of temperature dependence of conductivity and magnetoresistance allows to find independently the density of states and the localization radius.

The AC conductivity of disordered semiconductors through localized states due to hopping conduction. In these experiments, the resistivity of the samples described by Mott hopping conductance with variable hopping described by formula (1), since there are linear dependence \( \ln(\rho) = f(T^{-1/4}) \) for samples shown in Fig. 5,6 at low temperatures

\[
\rho = \rho_0 \exp \left( \frac{T_0}{T} \right)
\]

The value \( n \) in equation (1) for 3-dimensional space and a constant density of states at the Fermi level \( g(E_F) = \text{const} \) is equal to 1/4 and the parameter \( T_0 \) is defined by the following expression

\[
T_0 = \frac{17.6}{g(E_F) a^3 k_B}
\]
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In hopping conduction is described by Pollack relation, in which one of the main features is that in the hopping conduction is involved only two centers, while an influence of the rest centers can be neglected. Then the conductivity describes by following equation [8]:

$$\sigma(\omega) = \frac{2^3}{96} e^2 kT [N(E_F)]^2 a^{-5} \omega [\ln \left( \frac{V_{pol}}{\omega} \right)]^4$$  \hspace{1cm} (4)

The calculations according to the above equations (1) (3) allowed to calculate the parameter $T_0$ and localization radius: $a = 8.63$ nm and $5.8$ nm, respectively. Using the equation (4) and obtaining from frequency dependences shown in Fig.7 radius of localization, one can calculate density of states at the Fermi level $N(E_F)$. According to [8] distribution of trap states near the Fermi level can be expressed by the equation

$$\frac{4}{3} \pi R^2 N_f (\Delta W / 2) = 1$$  \hspace{1cm} (5)

Carrier jumping occur in a narrow energy region ($\Delta W = 1.22$ meV, $a=8.63$ nm, $g(E_F) = 8.96 \times 10^{15}$ eV cm$^{-3}$, $8.68<R<10$ nm) for samples with $\rho_{300K} = 0.0168$ Ohm$\times$cm, and ($\Delta W = 1.16$ meV, $a=5.8$ nm, $g(E_F) = 9.8 \times 10^{17}$ eV cm$^{-3}$, $5.9<R<6.2$nm) for samples with $\rho_{300K} = 0.0143$ Ohm$\times$cm.

At charge carrier transport due to hopping conduction through localized in the bandgap states it should be noted that these localized states are randomly distributed in the sample volume and are divided by the energy barrier. The value of the parameter $s$ in the frequency dependence of conductivity allow to evaluate the energy difference between the ground and free states, in which charge carrier can move through the crystal

$$W_m = \frac{6kT}{1-s}$$  \hspace{1cm} (6)

Fulfilled calculations showed that in the sample $W_m = 9$ meV. This value and the value crystal dielectric constant at high frequencies, where $\sigma \sim \omega^{0.8}$, allow to estimate localization radius by the following equation:

$$a = \frac{e^2}{2e^2 F_N W_m}$$  \hspace{1cm} (7)

To determine the whole activation energy region it was held differentiation of temperature region of the resistivity:

$$\varepsilon = \frac{d \ln \rho}{d(1/kT)}$$  \hspace{1cm} (8)

The dependence of resistivity on inverse temperature is shown in Fig. 9,10. Using equations 8 and the data from the linear plot according $\rho(T^{-1})$ it was obtained the following numerical values of the activation energy: $\varepsilon = $
2.3 meV for samples with resistivity \( \rho_{300K} = 0.0168 \) Ohm cm and \( \varepsilon = 1.86 \) meV for samples with resistivity \( \rho_{300K} = 0.0143 \) Ohm cm, respectively.

**Conclusion**

Analyzing the data obtained from the temperature dependence of conductivity it was showed that at high temperatures the conductivity is determined mainly by carrier thermoactivation carriers with activation energy of 1.86 ± 2.3 meV. At lower temperatures 4.2-20 K the conductivity occurs due to hopping transport of charge carriers in localized states that lie in a narrow band of energies near the Fermi level (hopping conductivity with variable hopping length). From the dependence of resistance on magnetic field it was determined the localization radius and density of localized states as well as the average length of carrier jump.

Obtained localization parameters from numerical calculations from DC measurements allow to calculate the radius of localization and jumping length for Si wires on the base of AC measurement. Carrier jumping occur in a narrow energy region \( (\Delta W = 1.22 \) meV, \( a=8.63 \) nm, \( g(E_F)=8.96 \times 10^{17} \) eV cm\(^{-3}\), \( 8.68<R<10 \) nm) for samples with \( \rho_{300K}= 0.0168 \) Ohm×cm, and \( (\Delta W = 1.16 \) meV, \( a=5.8 \) nm, \( g(E_F)= 9.8 \times 10^{17} \) eV cm\(^{-3}\), \( 5.9<R<6.2 \) nm) for samples with \( \rho_{300K}= 0.0143 \) Ohm×cm.