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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.

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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 2×10^{18} to 2×10^{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 there were obtained three groups of samples with boron impurity concentration corresponding to ρ_{300K}= 0.0143 Ohm×cm, ρ_{300K}= 0.0155 Ohm×cm, ρ_{300K}= 0.0168 Ohm×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 -

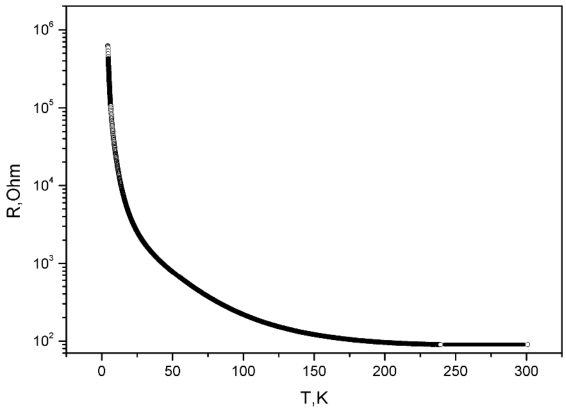

Fig. 1. Temperature dependence of samples with resistivity ρ = 0,0168 Ohm×cm.

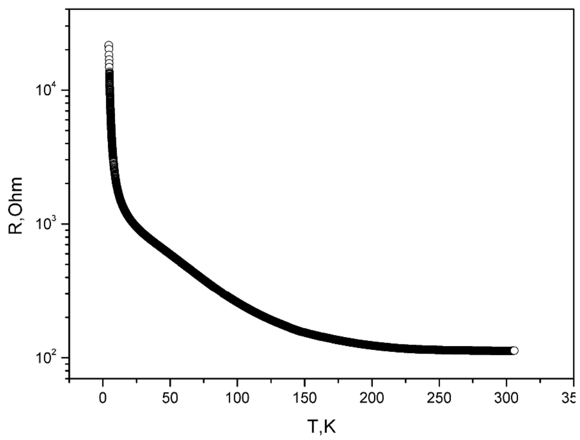

Fig. 2. Temperature dependence of samples with resistivity ρ = 0,0143 Ohm×cm.

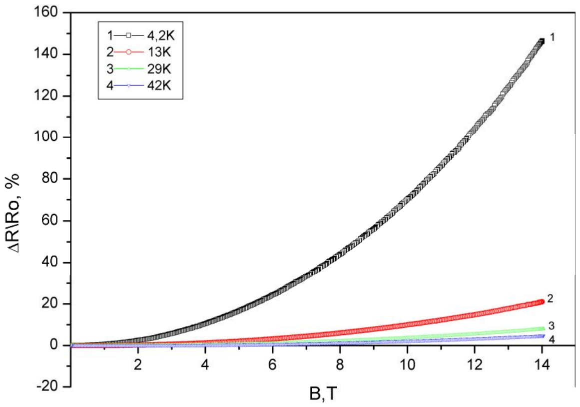

Fig. 3. Magnetoresistance of samples with resistivity ρ = 0,0168 Ohm×cm.

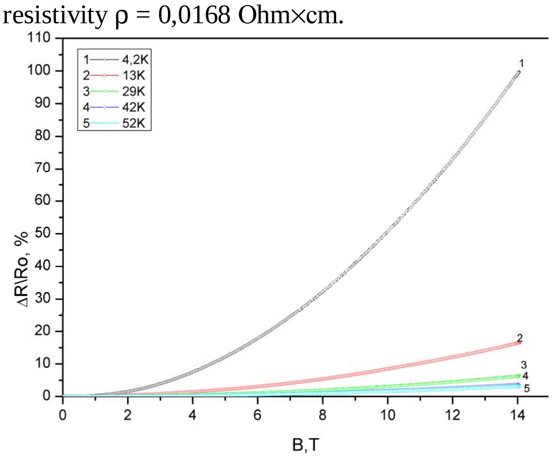

Fig. 4. Magnetoresistance of samples with resistivity ρ = 0,0143 Ohm×cm

70K.

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) low-temperature electron transport occurs by tunneling jumps with variable hopping impurity with radiation or absorption of phonons[7]. As it is known at low temperatures electron transport occurs through localized states due to hopping conduction. In these experiments, the resistivity of the samples described by Mott hopping conductance with variable hopping descrihing by formula (1), since there are linear dependence ln (ρ) = f ($T^{-1/4}$) for samples shown in Fig. 5,6 at low temperatures

$$\rho = \rho_0 \exp\left(\frac{T_0}{T}\right)^n \qquad (1)$$

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

$$T_0 = \frac{17.6}{g(E_F)a^3 k_B} \qquad (2)$$

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

$$\ln\left(\frac{\rho(H)}{\rho(0)}\right) = \frac{5}{2016} a^4 H^2 (T_0/T)^{3/4} / (c^2 \mathbf{h}^2) \qquad (3)$$

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

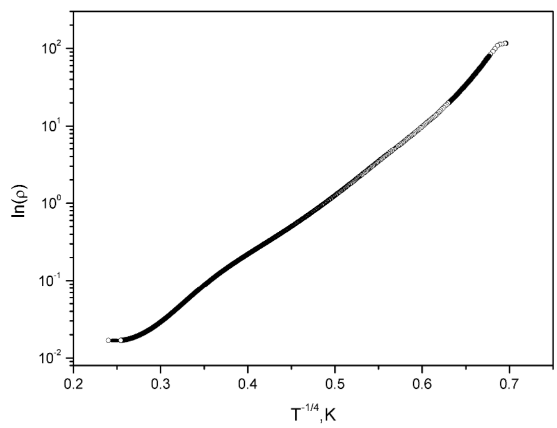

Fig. 5. Mott law resistance dependency for the sample with room temperature resistivity ρ = 0,0168 Ohm×cm.

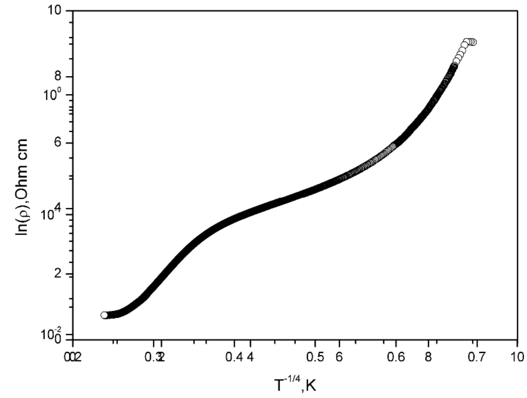

Fig. 6. Mott law resistance dependency for the sample with room temperature resistivity ρ = 0,0143 Ohm×cm.

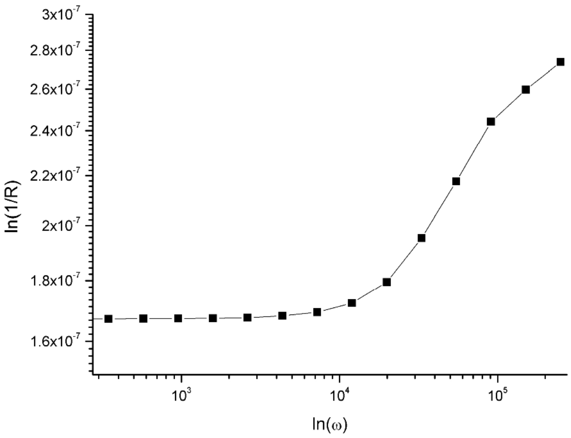

Fig. 7. Dependency of Si wire resistivity on frequency for sample with room temperature resistivity ρ=0,0168 Ohm×cm.

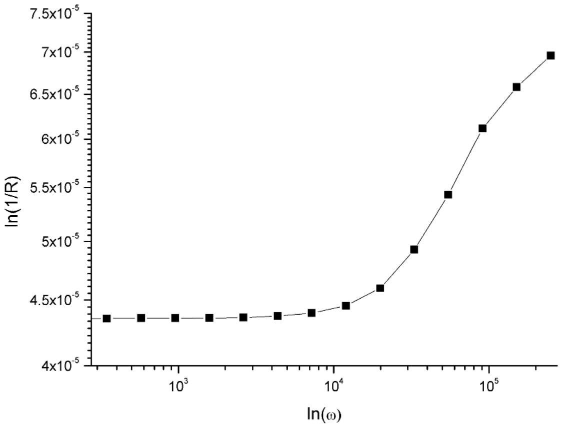

Fig. 8. Dependency of Si wire resistivity on frequency for sample with room temperature resistivity ρ = 0,0143 Ohm×cm.

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]:

$$\sigma(\omega)=\frac{\pi^3}{96}e^2\,kT[N(E_F)]^2\,a^{-5}\,\omega[\ln\left(\frac{\nu_{фон}}{\omega}\right)]^4 \qquad (4)$$

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

$$(4/3)\pi R^3\,N_F\,(\Delta W/2)=1 \qquad (5)$$

Carrier jumping occur in a narrow energy region (ΔW = 1,22 meV, a=8.63 nm, $g(E_F)$=8,96 10^{17} eV cm^{-3}, 8.68<R<10 nm) for samples with ρ_{300K}= 0,0168 Ohm×cm, and (ΔW = 1.16 meV, a=5.8 nm, g (E_F)= 9.8 10^{17} eV cm^{-3},5.9<R<6.2nm) for samples with ρ_{300K}= 0,0143 Ohm×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

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

Fulfilled calculations showed that in the sample Wm = 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:

$$a=\frac{e^2}{2\varepsilon_0\varepsilon\,W_m} \qquad (7)$$

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

$$\varepsilon=\frac{d\ln\rho}{d(kT)^{-1}} \qquad (8)$$

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: ε =

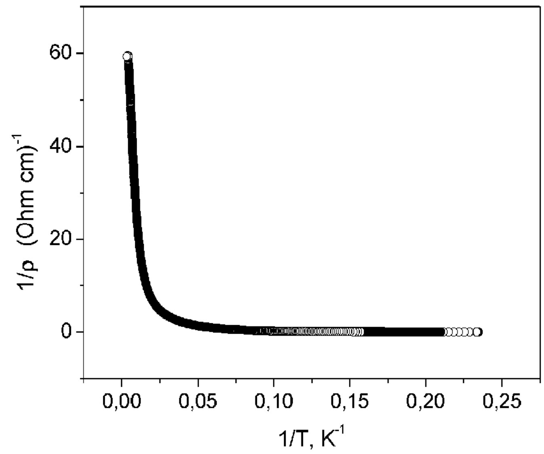

Fig. 9. Dependency of Si wire resistance for samples with room temperature resistivity ρ = 0,0168 Ohm×cm.

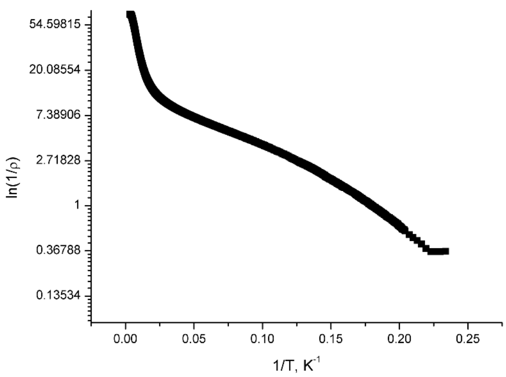

Fig. 10. Dependency of Si wire resistance for samples with room temperature resistivity ρ = 0,0143 Ohm×cm.

2,3 meV for samples with resistivity ρ_{300K} = 0,0168 Ohm cm and ε = 1.86 meV for samples with resistivity ρ_{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 thermoacttivation 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 (ΔW = 1,22 meV, a=8.63 nm, $g(E_F)$=8,96 10^{17} eV cm^{-3}, 8.68<R<10 nm) for samples with ρ_{300K}= 0,0168 Ohm×cm, and (ΔW = 1.16 meV, a=5.8 nm, $g(E_F)$= 9.8 10^{17} eV cm^{-3},5.9<R<6.2nm) for samples with ρ_{300K}= 0,0143 Ohm×cm.

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