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Transport Phenomena for Development Inductive Elements Based on Silicon Wires

A.A. Druzhinin[1,2*], I.P. Ostrovskii[1], Yu.M. Khoverko[1,2], R.M. Koretskyy[1], M.Yu. Chernetskiy[1]

[1] *Lviv Polytechnic National University, 12, S. Bandera Str., 79013 Lviv, Ukraine*
[2] *Institute of Low Temperature and Structure Research, Wroclaw, Poland*

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Conductance and magnetoresistance of Si < B > whiskers with diameters 5-40 μm doped with boron impurity were investigated in temperature range 4.2 ÷ 300 K, frequency range $1 \div 10^5$ Hz and magnetic fields with intensity up to 14 T by method of impedance spectroscopy. Hopping conductance on impurity states was shown to be realized in the crystals in low temperature region. The studies allow us to obtain parameters of hopping conduction. On the basis of experimental results a miniature inductive element was created using silicon wire.

Keywords: Silicon wires, Impedance spectroscopy, Metal-insulator transition, Inductive element.

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1. INTRODUCTION

Variable-range hopping conductance is of great importance studies in low dimensional structures [1-4]. At the same time, silicon whiskers make it possible to vary the perfection of the structure within wide limits, and thus to simulate different conditions for checking and clarifying existing representations and obtaining new data on the physical nature of many processes occurring in solids [5].

The basis of the measurement of these characteristics is the determination of the electrical conductivity of the crystal, which varies under the influence of the external factor (temperature, pressure, deformation) [6]. Therefore, the study of the behavior of the electrical conductivity of the crystals is an important fundamental and practical task.

On the other hand, to predict the characteristics of the sensors it is important to know the concentration of alloying impurities in silicon crystals, which are difficult to determine by direct methods (Hall studies) due to the complexity of manufacturing Hall contacts to crystals of small diameter [7].

The use of an alternating signal (sinusoidal or pulse) makes it possible to neglect the interference from the industrial network and the thermo-e.r.f., that arise when dealing with heterogeneous materials, as well as in cases of measuring dynamic signals that change in time [8, 9]. The present work deals with studies of Si wire resistance at alternating current with frequency 0.01-250 kHz in temperature range from 4.2 to 300 K. The conducted investigations allow us to create miniature inducted element based on Si wire (see chapter 3).

2. EXPERIMENTAL RESULTS

Silicon wires crystals were grown by chemical vapor deposition method in vacuumed ampoules with bromine 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 crystals, doped boron with concentration up to $\rho_{300K} = 0.0143$ Ohm·cm, $\rho_{300K} = 0.0155$ Ohm·cm, $\rho_{300K} = 0.0168$ Ohm·cm in the dielectric side of the metal-insulator-transition (MIT). Frequency dependence of resistivity for Si whiskers was obtained by frequency generator in the range 0.01-250 kHz at various temperatures in the range from 4.2 to 70 K.

Temperature dependencies obtained at constant current in temperature range 4.2-300 K for typical samples are shown in Figures 1, 2.

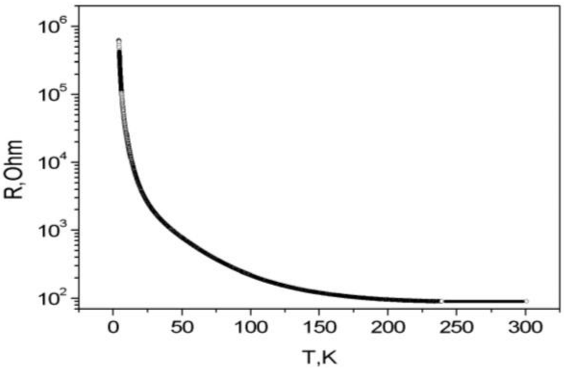

Fig. 1 - Change in the resistance for Si whiskers samples versus temperature with $\rho = 0.0168$ Ohm·cm

The transfer of charge carriers at low temperatures is due to hopping tunneling (in accordance with the Mott law) with a variable length of the jump with simultaneous absorption or phonon emission [10].

As it is known at low temperatures electron transport occurs through localized states due to hopping

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[*] druzh@polynet.lviv.ua

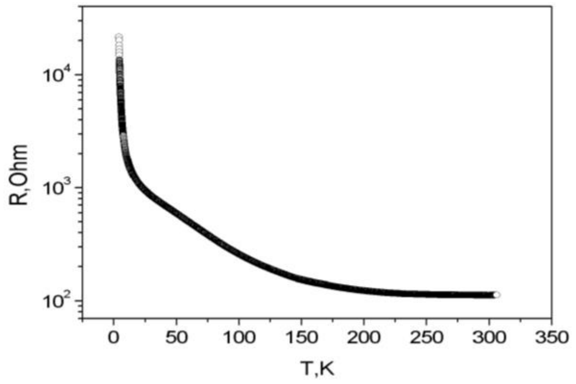

Fig. 2 - Change in the resistance for Si whiskers samples versus temperature with $\rho = 0.0143$ Ohm·cm

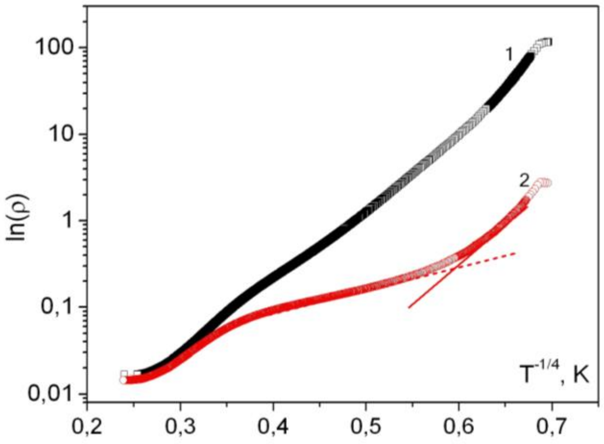

Fig. 3 - Change in the resistivity for Si whiskers samples versus temperature (in accordance with the Mott law) with $\rho_{300K} = 0.0168$ Ohm·cm (1) $\rho_{300K} = 0.0143$ Ohm·cm (2)

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 $ln(\rho) = f(T - 1/4)$ for samples shown in Figures 3 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 $g(EF) \approx$ 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 – localization radius of the wave function. This component of the magnetoresistance due to compression of the wave function in magnetic field is determined by following equation:

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

As follows from the equations (1-3), at synchronous experimental investigation of dependence of conductivity and magnetoresistance [6] versus temperature it is possible to find the density of states and the localization radius charge carries.

The conductivity of Si crystal by alternating current within the framework hopping conduction is described by Pollack relation, which takes into account hopping tunneling only between the two centers. Then the conductivity describes by following equation [11]:

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

The calculations according to the above equations (1)-(3) allowed to calculate the parameter T0 and localization radius: $a = 8.63$ nm and 5.01 nm, respectively. Using the equation (4) and obtaining, for example, from frequency dependences shown in Fig. 4 radius of localization, one can calculate density of states at the Fermi level N(EF). 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 ($\Delta W = 1.22$ meV, $a = 8.63$ nm, $g(E_F) = 8.96\ 10^{17}$ eV cm^{-3}, $8.68 < R < 10$ nm) for samples with $\rho_{300K} = 0.0168$ Ohm · cm, and ($\Delta W = 1.16$ meV, $a = 5.8$ nm, $g(E_F) = 9.8\ 10^{17}$ eV cm^{-3}, $5.9 < R < 6.2$nm) for samples with $\rho_{300K} = 0.0143$ Ohm·cm.

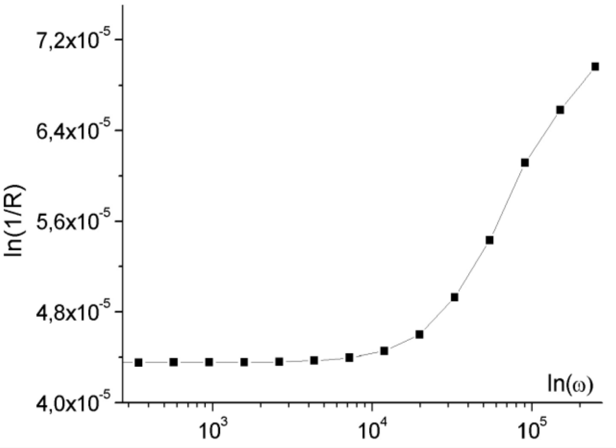

Fig. 4 - Frequency dependence of conductivity for Si crystal (in accordance with the Mott law (AC)) with resistivity $\rho_{300K} = 0.0143$ Ohm·cm

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. Knowing the parameter s, which can be estimated from experimental studies of the frequency dependence of allow to evaluate the energy difference between the ground and free states:

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

Fulfilled calculations showed that in the sample $W_m = 3$ 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:

$$a = \frac{e^2}{2\varepsilon_0 \varepsilon\ W_m} \tag{7}$$

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

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

Similar results for hopping tunneling in the temperature region 4.2 K were obtained by the authors of works [12, 13], however, the features of the low-temperature transfer of charge carriers in the material are due to the presence of trapping states at the grain boundaries in the polycrystalline material.

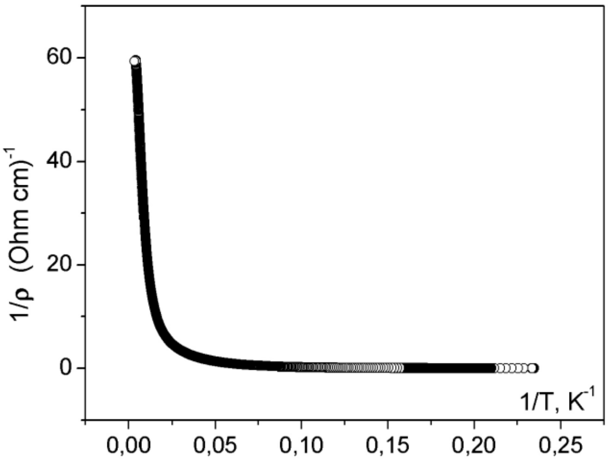

Fig. 5 – Change in the resistivity for Si whiskers versus reverse temperature with ρ_{300K} = 0.0168 Ohm·cm

Change in the resistivity for Si whiskers versus reverse temperature is shown in Figure 5, 6. According to equations (8) and the data from the linear plot with $\rho(T-1)$ it was received the value of the activation energy: ε = 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.

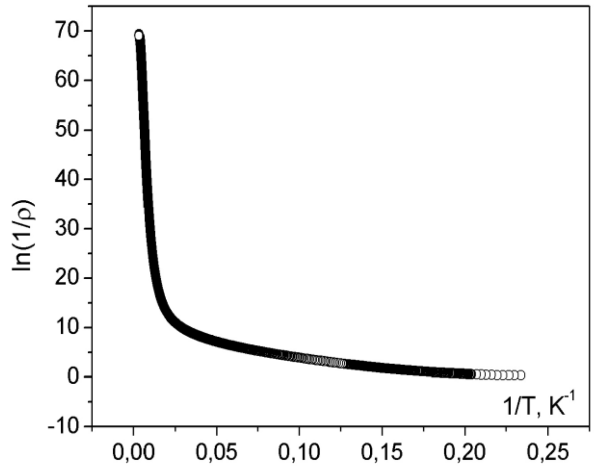

Fig. 6 – Change in the resistivity for Si whiskers versus reverse temperature with ρ_{300K} = 0.0143 Ohm·cm

The results of calculations of the parameters of low-temperature transfer of charge carriers according to experimental data samples are summarized in Table 1.

Table 1 – Crystal parameters

ρ_{300K}, Ohm·cm	$N(E_F)$, eV×cm^{-3}	R_{hop}, nm	a_{DC}, nm	a_{AC}, nm	W_{DC}, meV	W_{AC}, meV	W, meV
0.0143	9.8 10^{17}	5.8-6.5	5.8	18	1.16	2.6	1.8
0.0168	8.96 10^{17}	8.0-9.5	8.6	26	1.22	3.0	2.3

*were ρ_{300K} – resistivity of simple; $N(E_F)$ – density of states at the Fermi level, R_{hop} – long jump carriers; a the radius of localization of charge carriers at constant and alternating currents, respectively; W_{DC} – the activation energy of charge carriers, calculated from the experimental data on a DC; W_{AC} – the activation energy of charge carriers, calculated from the experimental data on a AC; W – the activation energy of charge carriers, obtained directly from experimental data.

3. DESIGN OF MINIATURE INDUCTIVE ELEMENT

As shown in Fig. 7, 8 for Si wires with impurity concentration, which corresponds to the vicinity to MIT, the Nyquist diagram reflects an inductive nature of the resistance in temperature range 4.2-300 K. A similar character was observed by the authors in [14, 15] in others compounds.

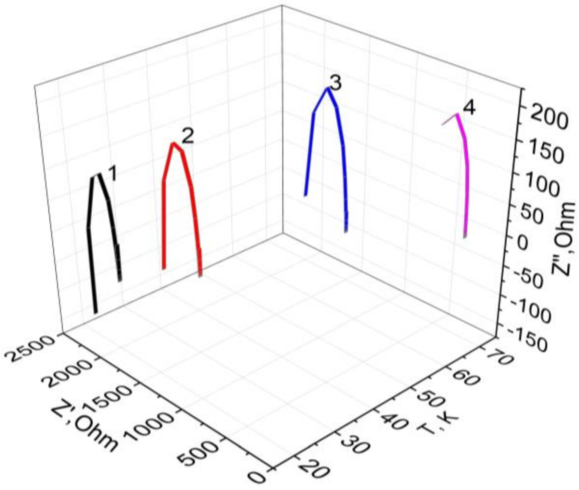

Fig. 7 – Nyquist diagram for Si wires (ρ_{300K} = 0.0168 Ohm·cm, d = 30 μm) at temperature: 1 – 4.2 K, 2 – 30 K , 3 – 60 K, 4 – 70 K

Explanation of the causes of the inductive nature of the impedance in Si wires samples is to look at the features of distributing alternating current in a thin whiskers. The distribution of impurities is uneven across the wire section, in particular the greater amount of impurities is concentrated near the surface [16, 17].

According to this effect the processes of captures and reradiations of free carriers by surface states take place, which results in relatively lagging current voltage. The result of the above described process is observed in the Nyquist diagram in the form of an inductive nature of the impedance [18].

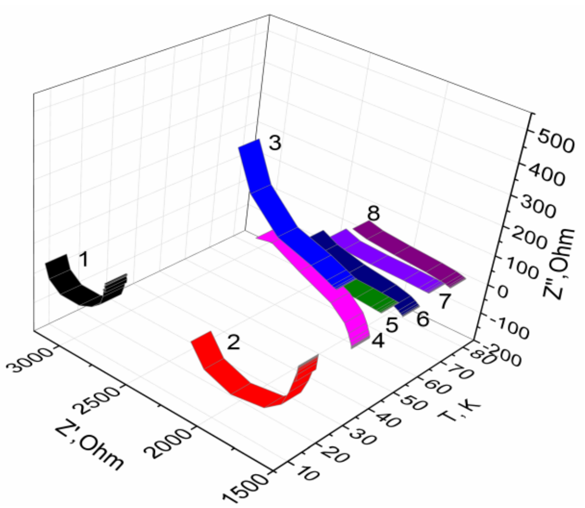

Fig. 8 – Nyquist diagram for Si wires (ρ_{300K} = 0,02 Ohm·cm, *d* = 30 nm) at temperature: 1 – 4.2 K, 2 – 10 K, 3 – 30 K, 4 – 40 K, 5 – 50 K, 6 – 60 K, 7 – 70 K, 8 – 80 K

The described effect was used for creating miniature inductive element on the basis of Si wires.

Figure 9 shows changes in figure of merit depending on frequency at temperature of liqiud helium for Si wire samples with boron concentration $1 \cdot 10^{19}$ cm^{-3}.

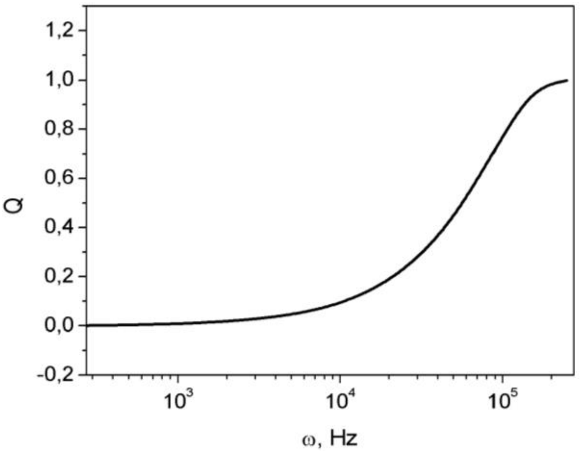

Fig. 9 – Dependence of figure of merit on frequency for Si wires at *T* = 4.2 K

The comparison between characteristics of inductive elements on the basis of Si wires and planar inductive elements of other manufacturers (See Table 2) shows that they have some advantages, including extended operating temperature range, much lower operating current value, high figure of merit, what indicates on their perspective application in microelectronics [19-20].

Table 2 – Characteristics of Semiconductor Inductive Elements

Manufacturer	Max inductance, mH	Q	Operating temperature range, K	Max current, μA	Operating frequency, kHz
Si (ρ_{300K} = 0.0168 Ohm·cm)	0.9	1.5	4.2-300	1	100
Si (ρ_{300K} = 0.0142 Ohm·cm)	0.7	1.3	4.2-300	1	100
Coilcraft	100	1	230-420	12.5	100
Panasonic	470	0.8	230-420	12.5	100
Toko	3300	1.1	230-420	27.2	100

Thus, the design of semiconductor inductive elements based on silicon whiskers together with simple technology allows to provide high output characteristics.

4. CONCLUSIONS

Analyzing the data obtained from the temperature dependence of conductivity it was showed that at relatively high temperatures the conductivity is determined by carrier thermoacttivation carriers with energy of 1.86 and 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). Experimental synchronous investigation of dependence of conductivity and magnetoresistance it was find the density of states and the localization radius charge carries 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.

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