Si, Ge and SiGe wires for sensor application

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***Abstract* – Resistance and magnetoresistance of Si, Ge and Si-Ge micro- and nanowires were studied in temperature range 4,2-300 K at magnetic fields up to 14 T. The wires diameters range from 200 nm to 20 μm. Ga-In gates were created to wires and ohmic I-U characteristics were observed in all temperature range. It was found high elastic strain for Ge nanowires (of about 0,7%) as well as high magnitude of magnetoresistance (of about 250% at 14 T), which was used to design multifunctional sensor of simultaneous measurements of strain and magnetic field intensity.**

Index Terms – InGa contacts, magnetoresistance, nanowires.

I. INTRODUCTION

Carrier transport in Si, Ge and their solid solutions, in particular in whiskers was studied in the works [1-3]. However, mechanism of carrier transport is not enough investigated at the range of cryogenic temperatures in the whiskers. Analysis of magnetoresistance character is one of the methods, which allows investigating conductance in the temperature range (4,2÷300) K. There are many works [4-6] devoted to theoretical and experimental studies of magnetoresistance in Si and Ge in the vicinity to metal-insulator transition (MIT). But all studies on measurements of magnetoresistance of Si, Si-Ge whiskers were conducted on crystals of large diameters > 50 μm [7-9]. Electric properties of Si, Ge nanowires are hard to measure due to a problem of ohmic gates fabrication. The convenient method for gate creation is well-known welding of Pt or Au microwire. But the method is not appropriated for nanowires due to their strain because of large gates.

The paper deals with an investigation of Si, Ge and Si-Ge micro- and nanowires resistance and magnetoresistance at temperature range 4,2-300 K in order to design sensors on their base.

II. EXPERIMENTAL RESULTS

The wires were grown as by chemical vapour deposition method and by melting in glass. The free standing Si, Si-Ge wires have diameters ranging from 5 to 20 μm, while Ge nanowires in glass envelope have diameters of 100-200 nm. The composition of Si-Ge solid solution was controlled in the whiskers by microprobe analysis: germanium content was 1÷**3** at. %. Electric gate to the crystals were made from Ga-In melt, freezing temperature of which is about 310K. The I-U characteristics were measured in temperature range 4,2-300 K. As have been shown the characteristics were ohmic in temperature range 77-300 K, while at low temperature a saturation of current was observed in Ge wires in glass envelope (see Fig.1). As obvious from Fig. 1 the saturation begin from the current value of 1 μA at 4,2 K. A current saturation observed is possibly explained by heating of sample due to bad heat sink through glass.

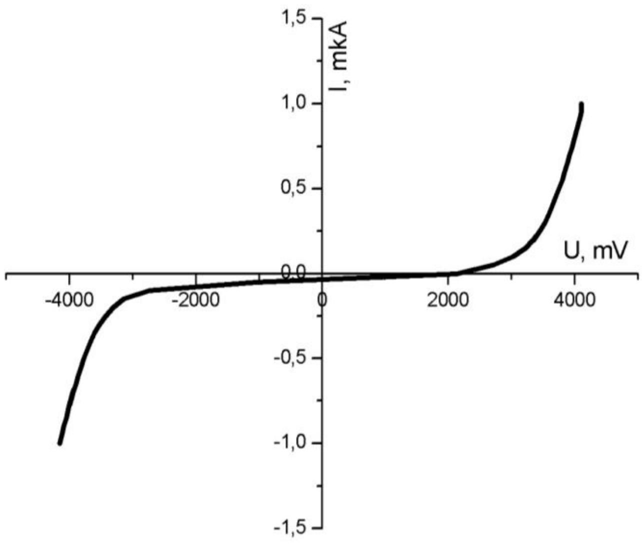

Fig.1. I-U characteristics of Ge nanowire (d=200 nm) at 4,2 K.

The crystals for investigations were selected with acceptor-impurity (boron) concentration closed to critical concentration of the metal-insulator transition both from metallic and dielectric side of the transition. The temperature dependences of wire conductance were measured for all samples in the temperature range (4,2÷300) K. The investigation of temperature dependencies of resistance for the wires of various diameters have shown substantial decrease of resistivity at the transition from dielectric to metallic samples (see Fig.2-4 for three typical Si, Ge, and Si-Ge wires).

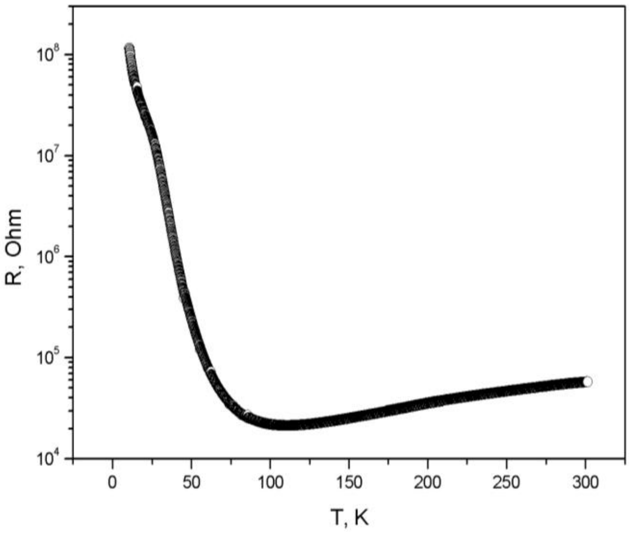

Fig.2. Temperature dependences of Ge nanowire (d=200 nm) resistance (ρ_{300K}=1,07 Ohm·cm)

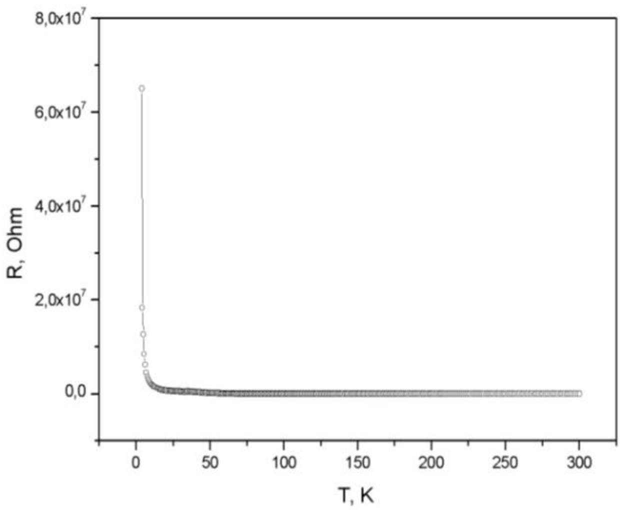

Fig.3. Temperature dependences of Si-Ge wire (d=20 μm) resistance (ρ_{300K}=0,02 Ohm·cm)

Wire magnetoresistance was measured at low temperature in the range of magnetic field 0÷14 T. The investigations reveal that magnetoresistance dependences $\Delta R_B/R$ as functions of magnetic field B are very different for the samples with different impurity concentration. The studies of the wires in magnetic field up to 14 T have shown a substantial change of magnetoresistance at the dielectric side of MIT – magnetoresistance changes from +250% for Ge wires to -1÷-2 % for Si-Ge wires (see Fig.5,6). For Si wires from metallic side of MIT linear dependency of magnetoresistance on magnetic field intensity was observed (see Fig.7).

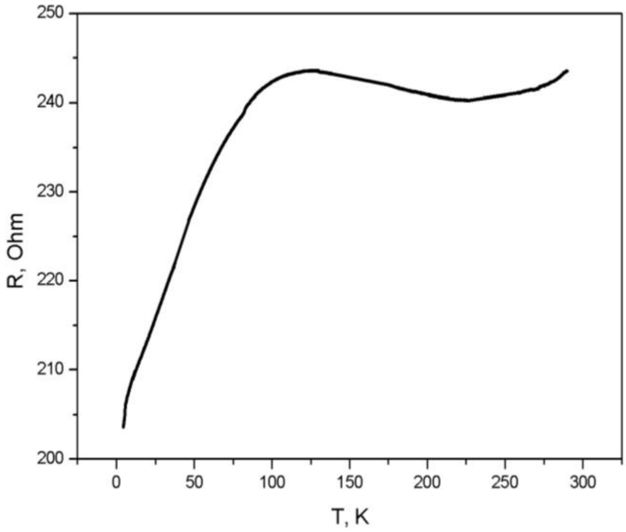

Fig.4. Temperature dependences of Si wire (d=5 μm) resistance (ρ_{300K}=0,01 Ohm·cm)

III. DISCUSSION

The quadratic dependence of whisker magnetoresistance as function of magnetic field is known [5] to correspond to band conductance, or localized state conductance in the Upper Habbard Band with the activation energy ε_2. The hopping conductance with the activation energy ε_2 = 3,8 eV really takes place for Si-Ge wires at temperature 4,2 K that is confirmed by the curve Fig.3 plotted in coordinates σ = f (1/T). An observation of quadratic field dependences of magnetoresistance in the samples (Fig.6, curve 1) indicates that their conductance occurs by localized states in the Upper Habbard Band.

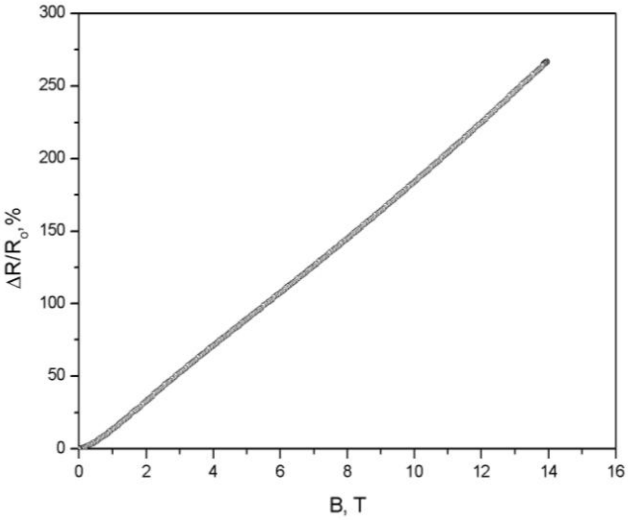

Fig.5. Field dependences of magnetoresistance for Ge nanowire (d=200 nm, ρ_{300K}=1,07 Ohm·cm, T=18 K)

An existence of NMR is typical for samples with impurity concentration in the vicinity to critical concentration of the MIT. We have found NMR in the Si-Ge wires from insulating side of the MIT (Fig.6, curve 2). In such samples NMR is known to occur due to carrier conductance by delocalizated states of Upper Habbard Band [10]. Activation energy of this conductance ε_2=4,5 meV was determined from temperature dependence of conductance at T>7 K in the samples. Therefore, in such samples NMR is expected to observe at higher temperatures (7-20K) as was confirmed by experiment.

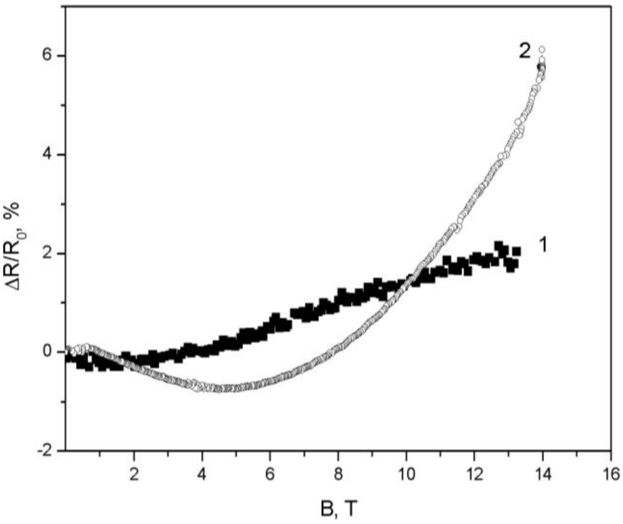

Fig.6. Field dependences of magnetoresistance for Si-Ge wire (d=20 μm, ρ_{300K}=0,02 Ohm·cm): 1 – 4,2 K, 2 – 6 K.

The exponential field dependence of magnetoresistance corresponds to conductance in the Lower Habbard Band with the activation energy $\square_3$ for insulating samples or to conductance with strong electron correlation in the metallic samples [11].

We have found an exponential field dependence of magnetoresistance for Ge wires from insulating side of the MIT. It should be noted that almost linear dependency of magnetoresistance on magnetic field intensity was observed (see Fig.5). Moreover one can

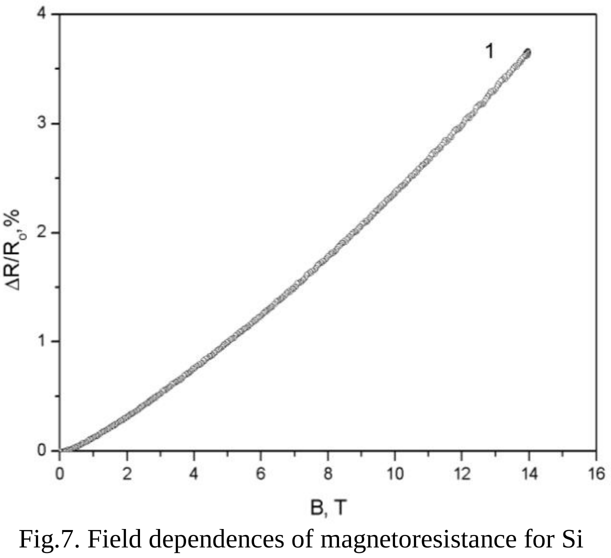

Fig.7. Field dependences of magnetoresistance for Si wire (d=5 μm, ρ_{300K}=0,01 Ohm·cm) : 1 – 4,2 K, 2 – 6 K.

underline the very high values of magnetoresistance – of about 250% at 14 T. The prominent feature of Ge nanowires is a large values of elastic strain (of about 0,7 %). The results are of great importance for sensor application. From one side, we have linear field dependency of magnetoresistance, which can be easily accounted to design of sensor of mechanical values on the base of such wires. From another side, high magnitude of magnetoresistance (of about 250%) can be used for design of sensor of magnetic field. So, two functional sensors for simultaneous measurement of magnetic field intensity and strain can be designed on the base of Ge nanowires.

Effects of electron correlation are likely to occur in metallic Si wires, in which exponential dependences of magnetoresistance are found (Fig. 7). As you can see from Fig.7, linear dependency of magnetoresistance was observed too. But in this case the magnitude of maximum magnetoresistance at 14 T is very small (of about 5% at 4,2K). The letter value essentially reduces at temperature decrease. So, Si wire can be successfully used for design of temperature sensors for low temperature range (4,2 – 77 K) (see Fig. 4).

IV. CONCLUSIONS

The paper deals with investigations of resistance and magnetoresistance of Si, Ge and Si-Ge micro- and nanowires (d=200 nm – 20 μm) in temperature range 4,2-300 K at high magnetic field up to 14 T. The study was possible due to a creation of Ga-In gates to micro-nanowires, which show ohmic contacts in the investigated range of temperatures. The crystals for investigations were selected with acceptor-impurity (boron) concentration closed to critical concentration of the metal-insulator transition both from metallic and dielectric side of the transition.

As a result of studies it was found NMR in the Si-Ge wires from insulating side of the MIT, which is shown to occur due to carrier conductance by delocalizated states of upper Habbard band. The investigations reveal linear dependence of magnetoresistance on magnetic field intensity for Ge (d=200 nm) and Si (d=5 μm**)** wires, that is important for sensor applications. So, high elastic strain for Ge wires (of about 0,7%) as well as high magnitude of magnetoresistance (of about 250% at 14 T) allow us to design of multifunctional sensor of simultaneous measurements of strain and magnetic field intensity. Linear dependence of resistance for Si wires is prominent for temperature sensor design operating in temperature range 4,2 – 77 K.

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REFERENCES

[1] Druzhinin A., Lavitska E., Maryamova I. et al. Studies of Pieoresistance and Piezomagnetoresistance in Si Whiskers at Cryogenic Temperatures // Cryst.Res. Technol. 2002, Vol.37. – P.243-257.

[2] Druzhinin A., Hortynska I., Maryamova I., Lavitska E. et.al. Investigation of free and strained germanium whiskers at cryogenic temperatures // Proceedings SPIE, 2000, Vol.4413. – P. 143– 147.

[3] Druzhinin A., Ostrovskii I., Liakh N. Study of piezoresistance in Ge_xSi_{1-x} whiskers for sensor

application // Materials Science in Semiconductor Processing. – 2005. – № 8. – P. 193-196.
[4] Shklovskii B.I., Efros A.L. Electron Properties of Doped Semiconductors, Nauka, Moskow, p. 416,1979. (In Russian)
[5] Rafey E.El., S.A. El.-Atawy. Magnetoresistance of intermediate concentration n-Ge at helium temperature// Can. J. Phys., 1987, V.65.–P.88.
[6] Gastner T.G., Shafarman W.N. Brooks J.S., Martin K.P. The metal-insulator transiton in n-type Si in high magnetic fields// Solid State Phys, 1988, N5. – P.366.
[7] Druzhinin A., Ostrovskii I., Liakh N. Magnetoresistance of Ge-Si whiskers // Physics of Solid State. – 2003. – V. 4, N 3. – P. 485–490.
[8] Druzhinin A.A., Ostrovskii I.P., Kogut Iu.R., Warchulska J.K. Magnetoresistance and magnetic susceptibility of doped Si-Ge whiskers // Functional Materials.– 2007.– V.14, N 4.– P. 480–484.
[9] Druzhinin A.A., Pavlovskyy I.V. Strain dependency of magnetoresistance of Si whiskers in the field of metal-insulator transition // Abstract of V Interm. Conf. "Actual problems of semiconductor physics ". – Drobybych: "Kamenjar", 2005. – P. 216-217.
[10] Trofimov I.E., Denin A.I., Murzin V.P. Magnetoresistance in D^- band. Preprint, Moskov, 1989 (in Russian).
[11] Ionov A.N., Shlimak I.S. Kondo effect in degenerated germanium doped with nonmagnetic impurities // Physics and Technics of Semiconductors, 1977.– V. **11**, N4. – P.741-747 (In Russian).