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TEMPERATURE SENSORS BASED ON Si-Ge SOLID SOLUTION WHISKERS

Temperature dependencies of Seebeck coefficient for free and strained heavily doped Si-Ge whiskers were studied in temperature range 4,2-300K. A compressive strain was shown to substantially change temperature behaviour of Seebeck coefficient. The main peculiarity of such change is stability of Seebeck coefficient in a wide temperature range 10-100 K, that is prospective for the whisker application in sensors of cryogen temperatures. Sensors for measurement of cryogenic temperatures operating in high magnetic field on the base of the whiskers were designed. Simplified circuit diagrams of processing the signals from the sensors were presented.

Studies of Seebeck effect in heavily doped semiconductor crystals at low temperatures are prospective fundamental (investigation of such phenomenon as hopping conductance, phonon capture [1,2], etc.) and applicative problem (e.g., for design of temperature sensors [3]). In our previous papers [4] thermo-e.m.f. of heavily doped Si-Ge whiskers was studied in temperature range 4,2-300K under action of uniaxial strain. However, the main attention in these papers was paid to study of physical nature of strain inducted effects in $Si_{1-x}Ge_x$ (x=0,01-0,05) solid solution whiskers.

In the present paper studies of Seebeck coefficient in heavily doped $Si_{1-x}Ge_x$ (x=0,01-0,05) solid solution whiskers in temperature range 4,2-300K were fulfilled to design temperature sensors operating under the action of high magnetic fields.

Ge_xSi_{1-x} solid solution whiskers with p-type of conduction were grown in [111] direction from the vapour phase by chemical transport reactions. The whiskers were grown in a sealed bromide system with use of aurum and boron impurities. The temperature of the source zone was 1370 K, and the crystallization zone – (1070÷1150) K. Germanium content in whiskers was controlled by microprobe analysis and it makes $x = 0{,}01\div0{,}05$. Whiskers for investigation were selected with average diameters about 20÷50 micron and length of about 10-12 mm. The platinum contacts with width 30 micron to the whiskers were made by method of electric impulse welding. The thermal strain was carried out by whiskers' mounting on specially selected substrates due to the different thermal expansion coefficients of Ge-Si whiskers and substrate materials. The strain value $\varepsilon = -4{,}3\cdot10^{-3} \div +1{,}4\cdot10^{-3}$ a.u.

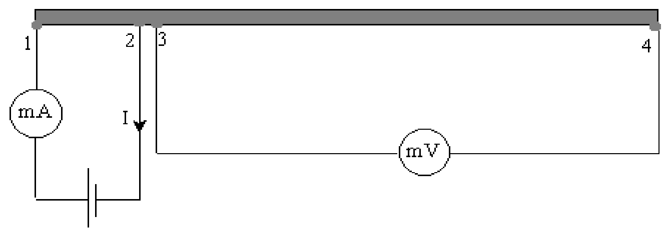

Fig. 1. A scheme of thermo-emf measurement for Si-Ge whiskers

Seebeck coefficient of the whiskers was measured by method shown on Fig.1 in the temperature range 4,2 –300K. Two electrical contacts 1 and 2 were used as heating branch (thermoresistor branch). Passing a current trough these contacts a gradient of temperature was created between the contacts 3 and 4. Then thermo-emf was measured between contacts 3 and 4. A distance between the contacts 2 and 3 was not exceed 200 μm, while a distance between the contacts 3 and 4 consisted of 10 mm. We determined temperature of hot end of the whisker by measuring of a resistance of thermoresistor branch and accounting its temperature dependency $R_{12}(T)$.

Measurements were carried out on SiGe whiskers with boron concentration in the vicinity to metal-insulator transition from dielectric side of the transition. Typical temperature dependencies of resistance for free and stained by various substrates whiskers with ρ=0,016 Ohm·cm are presented in Fig.2. The investigations have shown that a strain substantially influences on the thermometer performances of the crystals. As shown from Fig.2 a resistance of compressive strained ($\varepsilon = -3{,}8\cdot10^{-3}$ a.u.) whisker (ρ=0,016 Ohm·cm) changes in three orders of magnitude in the temperature range 10-50K. Besides, in this temperature range linear dependence lnR=f(T) occurs. For free whiskers with low doping level (ρ=0,025 Ohm·cm) abrupt change of a resistance (in 3-4 orders of magnitude) takes place too, but unlinearity of the dependency lnR=f(T) is essentially greater. Hence, use of specially strained heavily doped whiskers has obvious advantages at measurement of low temperatures.

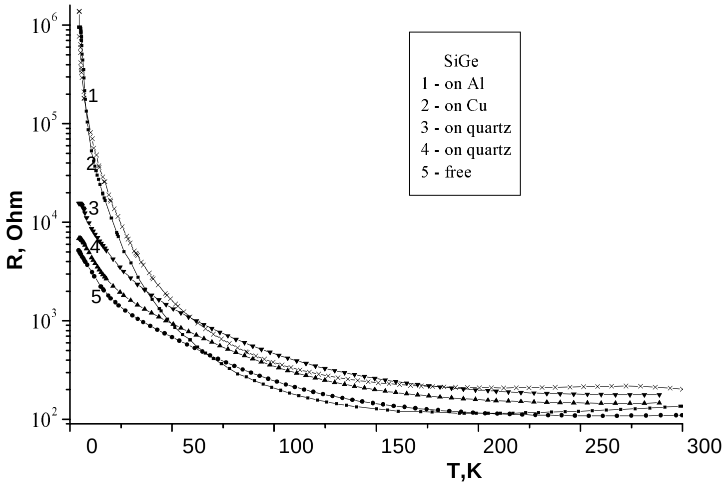

Fig. 2. Temperature dependencies of resistance for Si-Ge (ρ=0,016 Ohm·cm) whiskers strained by various substrates

Besides, temperature dependencies of Seebeck coefficient for free and strained samples were investigated in temperature range 4,2-300K (Fig.3). As it is obvious from Fig.3, stretch strain influences slightly on temperature behaviour of Seebeck coefficient, while compressive strain leads to its substantial change. The main peculiarity of such change is stability of Seebeck coefficient in a wide temperature range 10-100K, that is prospective for the whisker application in sensors of cryogen temperatures.

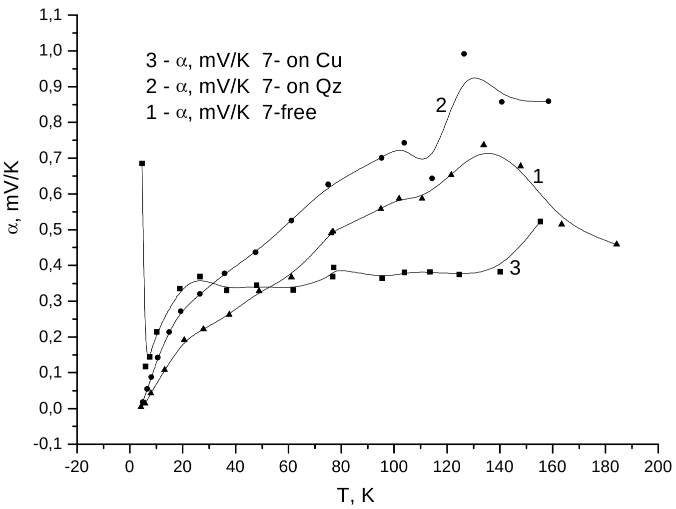

Fig. 3. Temperature dependencies of Seebeck coefficient for $Si_{1-x}Ge_x$ (x=0,03) whisekrs at various values of strain: 1 – ε=0; 2 – $+4{,}7\cdot10^{-4}$; 3 – $-4{,}3\cdot10^{-3}$

From a physical point of view existing of maximum in temperature dependence of α in free samples is explained by effect of phonon capture of charge carriers. A stretch strain slightly amplifies this effect, that leads to increase of maximal value of α. Compressive strain likely suppresses the effect of phonon capture, that can result from change of phonon spectrum of strained crystal.

On the base of results obtained a sensor for measurement of cryogenic temperatures was designed. In the sensor a thermoelectic branch is used for measurement of temperature difference, while a thermoresistor branch – for measurement of absolute temperature. The main peculiarity of the sensor is use of compressive strained Si-Ge whisker. Such a strain rises a sensitivity of thermoresistor branch, from one side, and provides a stable measurement of temperature difference, from the other side.

To illustrate the above a comparison of thermometer performances of strained and unstrained whiskers is fulfilled and presented in Table 1.

Table 1

A comparison of thermometer performances of strained and unstrained Si-Ge whiskers

Range of operating temperatures, K	TCR, %/K	Temperature sensitivity at T=7K, Ohm/K	Samples
4.2÷10	13÷16	300	unstrained
4.2÷50	6÷16	12 500	stained $\varepsilon = -3{,}8\cdot10^{-3}$ a.u.

As shown from Table 1, use of strained Si-Ge whiskers substantially widens range of operating temperatures and increases temperature sensitivity of thermoresistor.

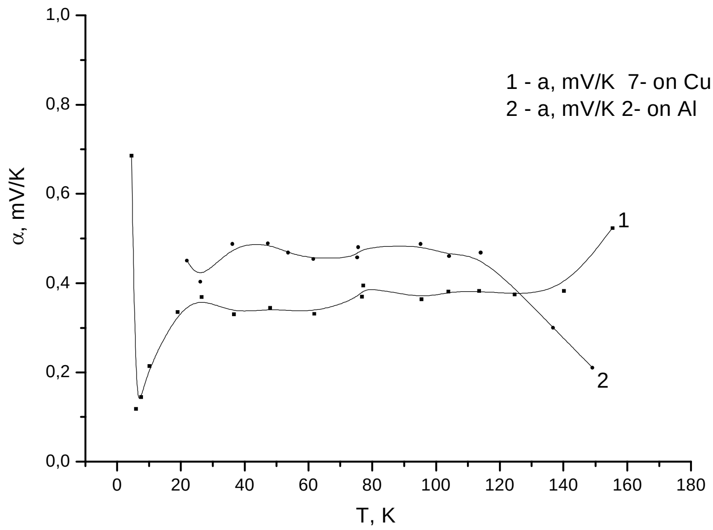

Fig. 4. Temperature dependencies of Seebeck coefficient for $Si_{1-x}Ge_x$ at various level of doping: 1 – ρ=0,016 Ohm·cm, x=0,03; 2 – ρ=0,025 Ohm·cm, x=0,05.

A compressive strain as already mentioned provides stability of Seebeck coefficient of the whiskers in wise temperature range. To optimize a sensor performances (broadening of operating temperature range and increase of temperature sensitivity) we carried out a set of measurements of temperature behaviour of Seebeck coefficient dependently on value of applied strain ($\varepsilon= -3{,}8\cdot10^{-3} – -4{,}3\cdot10^{-3}$), resistivity (ρ=0,016 – 0,025 Ом·см), and composition (x=0,01-0,05) of the whiskers. The results of these measurements are presented in Fig.4. As shown from Fig.4 all the samples have stable Seebeck coefficient in temperature range 10-100K. However, maximum of α = 0,47±0,02 mV/K is obtained for samples with ρ=0,025 Ohm·cm at a strain $\varepsilon= -4{,}3\cdot10^{-3}$ and x=0,05. At use of such a samples precision of measurement of temperature difference consists of ~ 0,1 K.

A design of sensor is very simple. It consists of $Si_{1-x}Ge_x$ (x=0,05) whisker with 40 μm in diameter with four Pt contacts (30 μm in diameter) (Fig.1). The whisker is glued by BF-2 on aluminium substrate. Temperature of hot end of the whisker is determined from thermometer performances (Fig.2) by measuring of resistance between the contacts 1 and 2. Precision of measurement of absolute temperature is about 0,2 K. Thermo-emf measured between the contacts 3 and 4 allows to determine a temperature difference between hot and cold ends of the whisker. Inertia of sensor at temperature measurement does not exceed 60 msec. Since a length of thermoresistor branch is about 200-300 μm and the whisker diameter is about 40 μm, the proposed sensor can serve as thermoprobe for measurement of temperature distribution on the surface of materials.

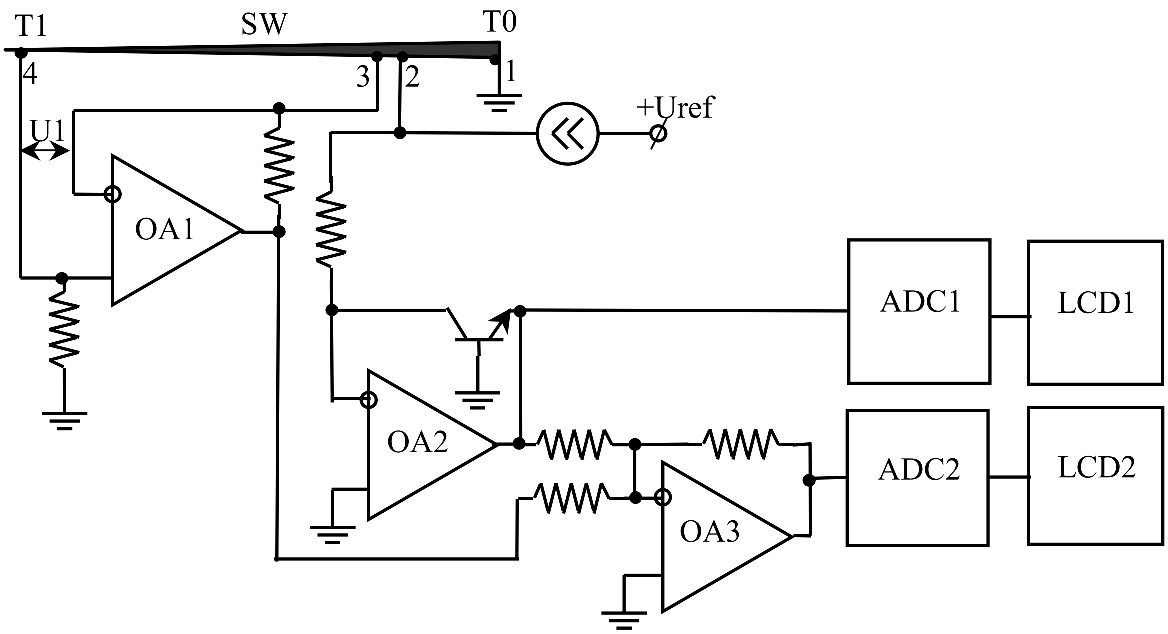

Fig. 5. Simplified circuit diagram of processing the signals from Si-Ge whiskers for the case when α(T) and ln(R_{12}) are linear with temperature

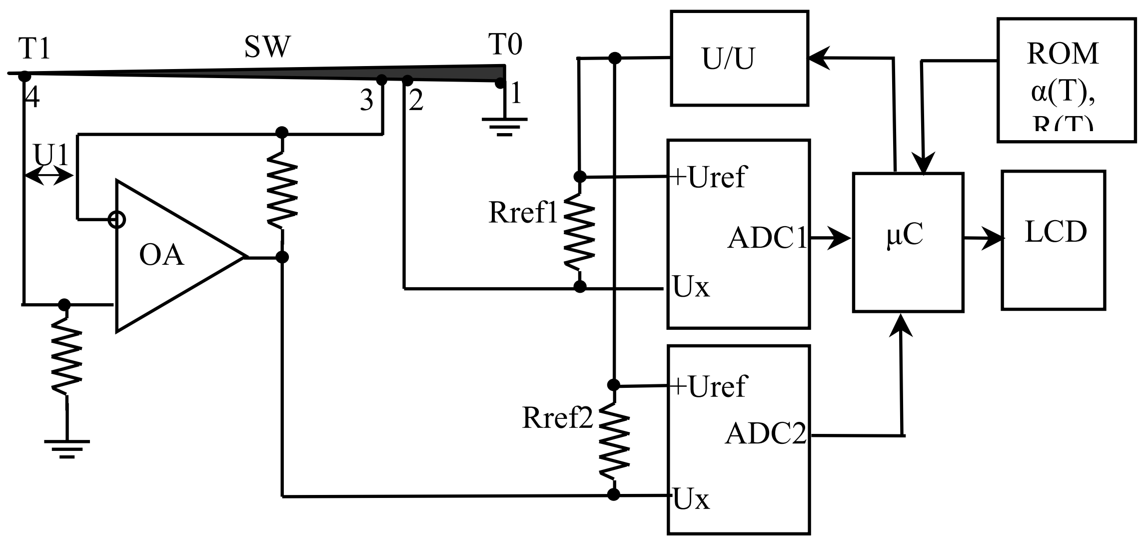

Fig. 6. Simplified circuit diagram of processing the signals from Si-Ge whiskers for the case when α(T) and ln(R_{12}) are nonlinear with temperature. Also we can use this circuit to extend the operating temperature range

The signal that we can get from temperature sensor shown on the figure 1 is not good for displaing and for the using in controlling systems. Before use this sensor we need convert the signal from temperature sensor into digital form. After that we can process, display and transmit it to other systems. For the compressive strained $Si_{1-x}Ge_x$ (x=0,05) whiskers where Seebeck coefficient α(T) is stable in temperature range 10-100K and $\ln(R_{12})$ are linear we can use the circuit diagram shown on the figure 5. On this circuit we have OA1 - Differential Amplifier for Ux; OA2 – Logarithmic Amplifier; OA3 – Adder; ADC – Analog to Digital Converter. OA1 forms thermo-e.m.f. Ux from whisker. OA2 find the logarithm of voltage which we get from thermoresistor branch R_{12} of whisker. OA3 adds the voltages from OA1 and OA2. Voltages from OA2 and OA3 are quantized by ADC1 and ADC2. LCD1 and LCD2 indicate proportional to the voltages temperatures T1 and T2.

For the $Si_{1-x}Ge_x$ whiskers where Seebeck coefficient α(T) and $\ln(R_{12})$ are nonlinear we can use the circuit diagram shown on the figure 6. Also we can use this circuit to extend the operating temperature range. In this circuit we have the microcontroller (μC) which process signals from the whisker end forms pulsed reference voltage that gives us possibility not use additional OA to amplify voltage from thermoresistor branch R_{12} of whisker. All measurements are perfomed in the high pulse of reference voltage which is formed in moment when ADC makes the conversion. In Read Only Memory (ROM) the α(T) and $\ln(R_{12}(T))$ are saved. Microcontroller calculates the temperatures T1 and T2 using α(T) and $\ln(R_{12}(T))$ arrays.

The investigations have shown that magnetic field (up to field with magnetic induction B=14 T) influences slightly on the magnitude and behaviour of temperature dependence of Seebeck coefficient and resistance of the whiskers, that enables us to use the sensor elaborated in strong magnetic fields. So, the results obtained allows to conclude that compressive strained $Si_{1-x}Ge_x$ (x=0,05) whiskers can be sucsessfully used for design of sensors for mesuring of cryogenic temperatures operating in the action of strong magnetic fields.

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