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THERMOELECTRIC PROPERTIES OF SiGe WHISKERS

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Background. $Si_{1-x}Ge_x$ solid solution whiskers with low germanium content have maximum ratio of mobility to the phonon thermal conductivity, which is promising for thermoelectrics. Thermal conductivity of SiGe nanowires is lower than of bulk samples that is also prospective for improvement of thermoelectric figure-of-merit and development of high efficiency thermoelectric microconverters. The temperature behavior of Seebeck coefficient of $Si_{1-x}Ge_x$ solid solutions whiskers in temperature range from 4.2 K to above room temperatures was studied. Peculiarities of whisker shape have been successfully used to determine their thermoelectric parameters, but these investigations were not conducted for SiGe solid solution whiskers.

Objective. The aim of the paper is study of possible influence of $Si_{1-x}Ge_x$ whisker geometry on their thermoelectric parameters.

Methods. SiGe whiskers were grown by CVD method in closed bromide system. The 3ω method was used to determine the temperature dependence of the thermal conductivity of $Si_{1-x}Ge_x$ ($x = 0.01$-0.05) whiskers in the temperature range 300-400 K. Resistance of whiskers was measured by a two-probe method. The resulting I-U characteristics of cross-shaped growths were used to determine the conductivity type of the whisker material.

Results. Seebeck coefficient and resistance was shown to increase, while thermal conductivity to decrease when the whisker diameter drops from 100 to 10 μm, that is accompanied by a rise of figure of merit (up to 0.12 at 300 K). Use of the whiskers with large obliquity leads to a small increase (of about 10-15 %) of their Seebeck coefficient.

Conclusions. Thermoelectric properties of $Si_{1-x}Ge_x$ ($x = 0.03$) solid solution whiskers doped with B impurities to the concentrations $1\cdot10^{17}$–$1\cdot10^{19}$ cm^{-3} were studied in temperature range 300-420 K. An influence of the whisker morphology, in particular their diameters and obliquity, on Seebeck coefficient, thermal conductivity and resistance was investigated.

Keywords: SiGe; whiskers; thermoelectric properties; Seebeck coefficient; thermal conductivity.

Introduction

$Si_{1-x}Ge_x$ solid solution whiskers with low germanium content have maximum ratio of mobility to the phonon thermal conductivity, which is promising for thermoelectrics [1–3]. Low values of thermal conductivity occur in nanowires due to presence of size effect [4] connected with phonon boundary scattering channel [5]. Despite of SiGe is good high temperature thermoelectric material, low thermal conductivity allows approaching high values of thermoelectric parameters even at low temperatures. For example, the thermal conductivity of silicon nanowires with diameters less than 30 nm and up to 115 nm were observed in the works [5] and [4, 6] in the temperature range 20-100 K and up to 300 K, respectively. The authors of work [6] have concluded that quantifying the surface roughness is crucial to studying of the phonon transport mechanisms and the thermoelectric device creation. High ZT values of 2D silicon structure could be obtained at room temperature by optimization of the doping level and effective surface passivation [7].

Use of facile conversion chemistry leads to enhanced thermoelectric performance [8] due to reduction of thermal conductivity. The reduction of thermal conductivity κ of thermoelectric materials is connected with possible their applications, it is also important for sensors of physical values that operate based on thermoelectric effects, because the temperature gradient should be maintained for their flawless operation. Thermal conductivity of $Si_{1-x}Ge_x$ solid solutions is determined by the element composition x [9–13], but it is still high (minimum of 12 W/(m×K) for bulk $Si_{0.7}Ge_{0.3}$ samples [9]. The dimensional features of samples, even in micron-scale solids with large length-to-diameter ratios, as whiskers, the κ decreases for certain Ge content. Thermal conductivity of SiGe nanowires turns to be 5 to 10 times lower than that of their bulk counterparts, approaching the theoretical amorphous limit [14–17]. This is prospective for substantial improvement of thermoelectric figure-of-merit of the nanoscale SiGe and development of high efficiency thermoelectric microconverters [18, 19].

We have studied in our previous works [20–22] temperature behavior of Seebeck coefficient of $Si_{1-x}Ge_x$ solid solutions whiskers in low temperature range – from 4.2 K to above room temperatures. The results showed a slight difference of the whiskers parameters from bulk materials. However, we have not considered the influence of the whisker geometry and shape on the thermoelectric properties, while it could be crucial as mentioned above [6, 7]. Certain results were obtained by us for Ge and Si whiskers, where it was shown that peculiarities of whisker shape could be successfully used for determination the whisker parameters [23, 24]. But investigations of the thermoelectric were not earlier conducted on solid solution SiGe whiskers.

Methodology of experiment

SiGe whiskers were grown by CVD method in closed bromide system [25]. The method provides the growth of the whiskers with unique mechanical parameters that widely used in sensors [26-28].

To adequately assess thermoelectric parameters of $Si_{1-x}Ge_x$ whiskers in certain temperature range it is important to know the real value of the coefficient of thermal conductivity κ. As is known, the parameter is highly dependent on the composition, degree of solid solution perfection. Therefore, we have tested 3ω method [29] to determine the temperature dependence of the whisker's thermal conductivity. The method consists in the following. Electric current of a certain frequency is passed through the whisker attached as a bridge on a dielectric thermal conductive substrate. The current heats the center of the crystal. Accordingly, the thermal conductivity flows from the center to the ends along the whisker axis. Heat flux at the air in these conditions can be ignored because it does not exceed 1% of the heat in the dielectric substrate. Solution of continuity equation by imposing certain boundary conditions that limited sample sizes and geometric value of the current flowing through the sample, can be written as follows [29].

$$V_{3\omega} = \frac{\sqrt{2} I_0^{\,3} R R' L}{\pi^4 \kappa S}, \tag{1}$$

where I_0 is the current with frequency ω, $V_{3\omega}$ is a voltage with frequency 3ω, R is the whisker resistance, R' is a change in resistance with temperature, L is the length of the crystal, S is cross-sectional area.

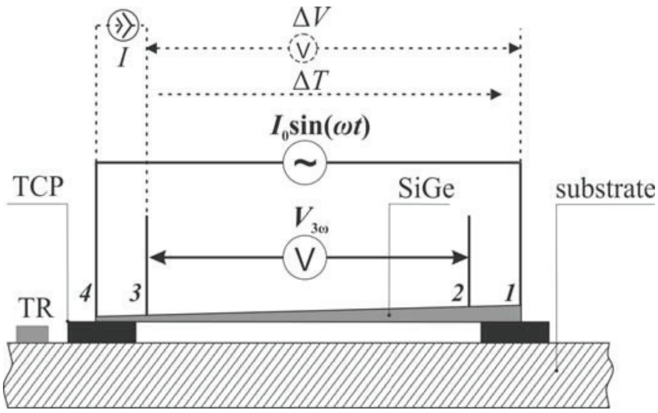

Fig. 1. Schematic view of the setting for thermal conductivity measurements by 3*ω*-method (solid lines) and for measurements of Seebeck coefficient (dashed lines) of SiGe whiskers. In the latter case, the part of whisker is heated by current *I*, which is passed between two adjacent electrodes (here, *3* and *4)*, and the thermo-e.m.f. Δ*V* induced due to temperature difference Δ*T* is measured between the hot and cold ends (here, *3* and *1*, respectively) [30].

Thus, the third harmonics voltage in the tested object inversely depends on its thermal conductivity, and the coefficient κ can be easily derived from the measurements of $V_{3\omega}$ signal developed between electrodes *2* and *3* (Fig. 1).

Thus, the voltage measured in the sample at a frequency 3ω is inversely proportional to the thermal conductivity of the crystal. This method was implemented to measure the thermal conductivity of $Si_{1-x}Ge_x$ (x = 0.01-0.05) whiskers in the temperature range 300-400 K [29].

The above-described setting has been used also for the measurements of Seebeck coefficient α of oblique p-type $Si_{1-x}Ge_x$ whiskers ($x = 0.01 – 0.05$) with boron concentrations ranging from 10^{17} cm^{-3} to 10^{20} cm^{-3}. The hot end has been heated by passing a current between two neighboring contacts, which induced the Joule heating of one of the ends, and the temperature was determined from the known $R(T)$ dependencies for studied SiGe whiskers, as described in [21]. Since active direct heating of whisker end was applied and a whisker-to-substrate thermal contact area was negligible in comparison with dimensions of virtually infinite substrate, the temperature gradient ΔT along the crystal could be easily maintained, even though the substrate was thermally conductive. To elucidate the effect of obliquity on thermopower of whiskers, the measurements were performed in such a manner that in one case the thickest part (*1 – 2*) was heated and in another – the thinnest one (*3 – 4*), as shown in Fig. 1. Resistance of whiskers was determined by a two-probe method, in which the readings obtained upon passing a current in two directions were averaged, and the resistivity was derived accounting for an effective cross-sectional area of oblique crystals. For measurements of temperature dependencies of thermal conductivity, thermopower and resistance the designed setting was placed inside the resistive furnace, and the temperature of the inset was determined by a thermoresistor attached to the substrate.

One can propose another method for thermoelectric parameters determination. The special conditions of the whisker growth (temperature regimes, oversaturation in gas phase, etc.) lead to creation of various aggregates with cross-like and X-like shape. In the paper we propose to use the whisker structures for estimation of certain thermoelectric parameters.

First of all, one can determine a type of conductance of semiconductor. For this purpose I-U curve of such cross-like aggregate should be measured. A growth of two whiskers with asymmetrical cruciform shape can be used. Applying a current to the longitudinal and measuring the voltage on the tansverse shoulders of the growth one can obtain C-type I-U characteristics (see Fig. 2).

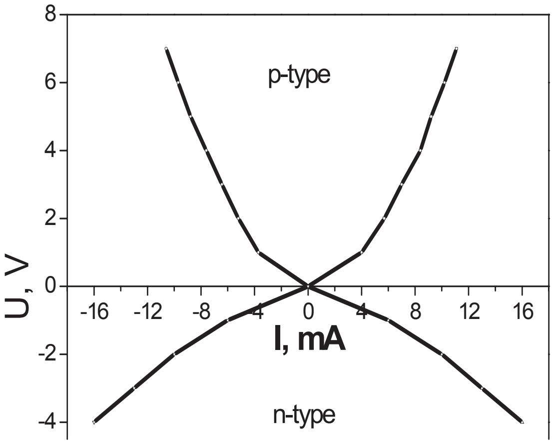

Fig. 2. I-U characteristics of Si-Ge whisker of p-type and n-type conductance.

Interestingly, the potentials measured at certain distances from node growths were positive in materials of p-type, or negative in n-type materials. Thus, the resulting I-U characteristics of cross-shaped growths can be used to determine the conductivity type of the whisker material.

Based on the studies it was developed method of determining the thermoelectric parameters of whiskers, which allows us to define other thermoelectric parameters of the crystals, in particular a ratio of Seebeck coefficient to thermal conductivity κ/α.

According to the proposed method, current is passed through a heating branch, namely two adjacent cross-shaped contacts of growth; two others contacts 1 and 2 serve as a measuring branch. The main measurable parameters were: 1) the potential difference U_1 and U_2 between the ends of measuring branch and the node of growth, 2) the impedance of measuring branch R_3 and 3) the current through measuring branch I_3.

Therefore, warming up the node of growth by current I_3 creates two heat flows from the growth middle to points 1 and 2 of the measuring branches that could be recorded as $W_1 = \frac{\kappa S}{l_1}\Delta T_1$ and $W_2 = \frac{\kappa S}{l_2}\Delta T_2$ (S- sectional area of the growth, l_1 and l_2 are the length of measuring branch, respectively).

Taking into account that temperature gradients ΔT_1 and ΔT_2 can be expressed due to value of thermopower $U_1 = \alpha \Delta T_1$ and $U_2 = \alpha \Delta T_2$, and the difference in heat flow creates between points 1 and 2 an electrical power, we get the equation

$$I_3^2 R_3 = \frac{\kappa S}{\alpha l_1}(nU_2 - U_1), \qquad (2)$$

where n= l_1/l_2.

The equation (2) allows us to determine the ratio of κ/α. The calculation were firstly successfully checked for Si whiskers. The results are presented in the Table 1.

Table 1 Thermoelectric parameters of cross-like Si whisker growths

I, mA heating current	U_1, 0-1 mV voltage difference	U_2, 0-2 mV voltage diference	R_3, Ohm resistance of measuring branch	I_3, μA heating current	κ/α, A/cm	α/κ, cm/A
50	49.0	33.8	224	9.6	4.2	0.24
60	73.5	57.5	242	11.6	4.05	0.26

The data of Table 1 shows that obtained value of *κ* /α consists of 4.1. The value was compared with data of [31] for bulk silicon at room temperature, which was equal to 4.6. Therefore, the results evidences that good agreement of our estimations with literature data was obtained.

Experimental results and discussion

Seebeck coefficient was investigated for $Si_{1-x}Ge_x$ (x = 0.03) whiskers doped with B impurity to concentration ranging from 10^{16} cm^{-3} to 10^{20} cm^{-3}. Seebeck coefficient values changes from 80 to 450 μV/K at room temperature dependent on the impurity concentration. Maximum value of α is found for whiskers with least carrier concentration. In the whiskers doped to the concentration 10^{16} cm^{-3} Seebeck coefficient increases from 440 to 500 μV/K in the temperature range 300-390K. Seebeck coefficient of samples with concentration 10^{17} cm^{-3} consists of about 400 μV/K at room temperature. When temperature increases weak enlargement of α is observed. Minimum α value is found for the whiskers with holes concentration 10^{20} cm^{-3}. At 300K α = 90μV/K.

The above methodological aspects allows us to estimate κ and α for $Si_{1-x}Ge_x$ (x = 0.03) whiskers in the temperature range 280-400 K. Firstly we presented the temperature dependence of Seebeck coefficient for the whiskers with 10^{17} cm^{-3} (see Fig. 1). Then taking into account the measured parameters of the whiskers growth we have obtained the following temperature dependences of coefficient of thermal conductivity (see Fig. 1).

As it is obvious from Fig.1, the samples doped with B impurity show temperature rise of Seebeck coefficient in the temperature range 300-400 K, slop and magnitude of α being dependent on impurity concentration. Atoms of B are known to create in $Si_{1-x}Ge_x$ (x = 0.03) forbidden gap shallow donor levels with ionization energy 0.042 eV. At room temperature these levels are completely ionizated. That is why character of α(T) dependencies in the measurable temperature range is corresponded to weak change of Fermi level position in the whiskers at temperature rise.

The obtained data of the whisker thermal conductivity (Fig. 3) are 3 times smaller than the correspondent parameters for bulk silicon. It is unexpectedly large change due to rather small composition of solid solution (x = 0.03). So, the obtained data should be checked by other direct measurement, in particular by 3ω method.

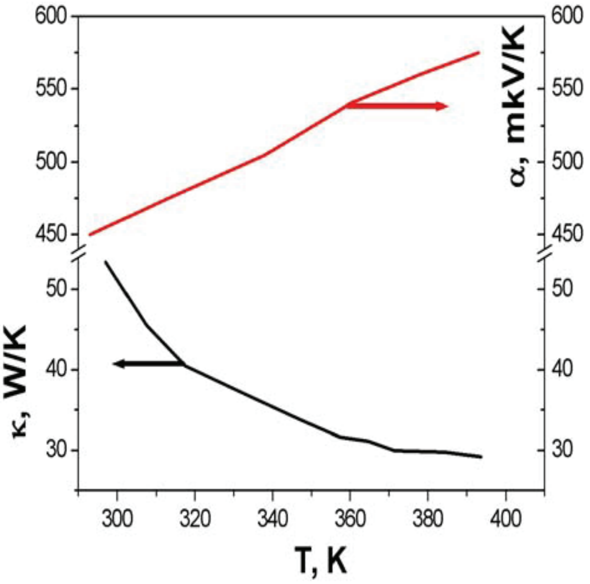

Fig. 3 Seebeck coefficient and thermal conductivity versus temperature dependency for $Si_{1-x}Ge_x$ (x = 0.03) whiskers with $p = 1\cdot10^{17}$ cm^{-3}

The observed rather small values of the whisker thermal conductivity are likely connected with peculiarities of the whisker geometry. To investigate the possible influence of the whisker shape we have obtained a size dependence of $Si_{1-x}Ge_x$ whisker Seebeck coefficient as well as its dependence on the whisker obliquity.

The dimensional dependency of Seebeck coefficient for Si-Ge whiskers was measured for whiskers with diameters ranging from 20 to 100 μm.

As it is obvious from Fig. 4, Seebeck coefficient of the whiskers rises at the decrease of their diameters. We have investigated the dimensional dependencies of the whisker resistance. The dependency shows that resistance rises at the whisker diameter decrease (Fig. 4).

As follows from our previous consideration enlargement of α is observed in the whiskers with a decrease of their impurity concentration (increase of their resistance). Thus, at the decrease of the whisker diameters their impurity content decreases *and* correspondingly their Seebeck coefficient rises as shown in Fig. 4.

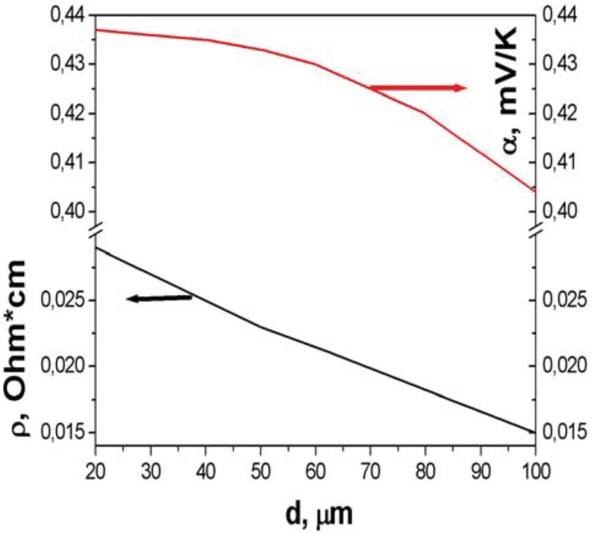

Fig. 4. Dimensional dependence of Seebeck coefficient and resistivity of $Si_{1-x}Ge_x$ (x = 0.03) whiskers (T = 300 K, $p = 1\cdot10^{17}$ cm^{-3})

One can obtain the similar dimensional effect when the samples with various obliquities are used. So we measured the Seebeck coefficient for the whiskers with different diameters of their ends. Heating of thick end of the whiskers gives substantially greater Seebeck coefficient as compared with the coefficient at heating of thin end of the whiskers. The obtained results of Seebeck coefficient change at heating of different ends of the whiskers (ΔT = const = 80 °C in the temperature range 20-100 °C) are shown in table 2.

Table 2. Seebeck coefficient change ($\Delta T = 80$ °C) in $Si_{1-x}Ge_x$ (x = 0.03) whiskers of various resistance and obliquity

№	ρ, Ohm·cm	Δl, µm	Δd, µm	K=Δd/2Δl	ΔU/U_c ×100%
1	0.06	13400	40	$1.50\cdot10^{-3}$	14.1
2	0.03	14500	40	$1.39\cdot10^{-3}$	11.3
3	0.03	6500	22	$1.74\cdot10^{-3}$	9.6
4	0.002	5600	31	$2.81\cdot10^{-3}$	5.1
5	0.002	4850	29	$2.98\cdot10^{-3}$	4.6
6	0.008	12200	45	$1.85\cdot10^{-3}$	4.6

As a rule, at heating of the thicker end of the whisker an obliquity impact (positive sign of $\Delta U/U_c$ parameter) was more significant. Dependence of the thermopower on the obliquity value K for different whisker sets could not observable - decisive factor plays a degree of the whiskers doping level.

Thus Table 2 shows that the greatest impact on the relative change of thermopower should not be caused by relative size of crystals but their resistivity. In fact the biggest changes of thermopower (up to 15%) were found in crystals with the highest resistivity of 0.06 Ohm cm, while the lowest one are their characteristic obliqueness of $1.50\cdot10^{-3}$.

Instead, the sample with the greatest obliquity of $2.98\cdot10^{-3}$, but with the lowest resistivity of 0.002 Ohm cm have rather small relative change in thermopower – only 5%.

For further analyze of the impact of size effects one can performe theoretical calculations of heat flow components W, that could be presented as superposition of the following contributions: W_1 is a flow through the whisker; W_2 is a flow in the substrate; W_3 is a convective flow in the air:

$$W = \frac{\kappa_1 d_1 + \kappa_2 d_2}{l} b_1 \Delta T + \alpha_T b_2 l (T_{ef} - T_o), \quad (3)$$

where κ_1 is coefficient of $Si_{1-x}Ge_x$ thermal conductivity; κ_2 is coefficient of thermal conductivity of substrate (0.233 W/mK) [8]; α_T is convective coefficient of heat transfer (100 W/m^2K) [20] T_o is ambient temperature (20 °C); T_{ef} is an effective temperature of the whisker surface (60 °C); d_1 – is an effective whisker diameter (~ √S), b_1 is an effective width of the whisker b_2 facet ($b_1 = 2.6a$, where a is the width of the whisker facet, $b_2 = 5a$); l is the whisker length; d_2 is substrate thickness ($2\cdot10^{-3}$ m)

One can neglect by third component associated with thermal radiation. According to the Stefan-Boltzmann effect its average value amounted to ~ $3\cdot10^{-9}$ W, which is rather small value as compare with other contributions. The results of calculation are presented in Fig. 5.

As you can see, heat flux W_2/W, called by heat conductivity in the substrate, is almost independent on the whisker width.

The other components are changed as follows. The heat flux due to the whisker thermal conductivity W_1/W substantially drops when the whisker width decrease from 100 to 10 µm. Convective heat flux W_3/W has inverse dimensional dependence: it decreases exponentially with the increase in the whisker size.

Thus, our calculations show that at decrease of the whisker diameter from 100 to 10 µm the total heat flow should decrease at 50% due to strong drop (in 3.5

times) of W_1/W and an increase (in 2.3 times) of W_3/W components.

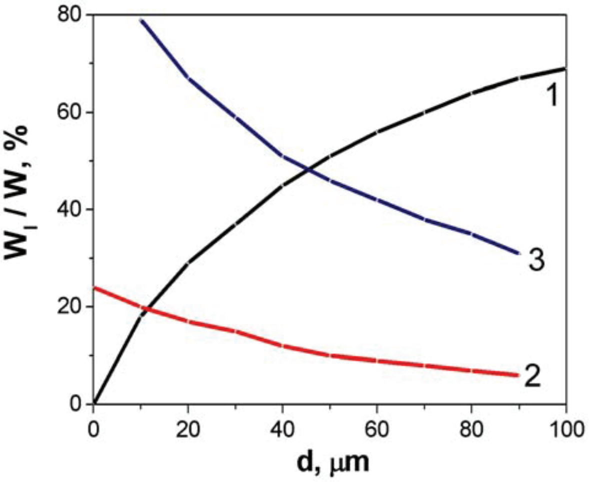

Fig. 5. Dependencies of heat flow components versus the width of the whisker:
1 - W_1/W is the heat flux due to whisker thermal conductivity;
2 - W_2 /W is a part of the heat flux due to heat conductivity in the substrate (the magnitude is x5);
3 - W_3/W is the heat flux due to convective flow in air

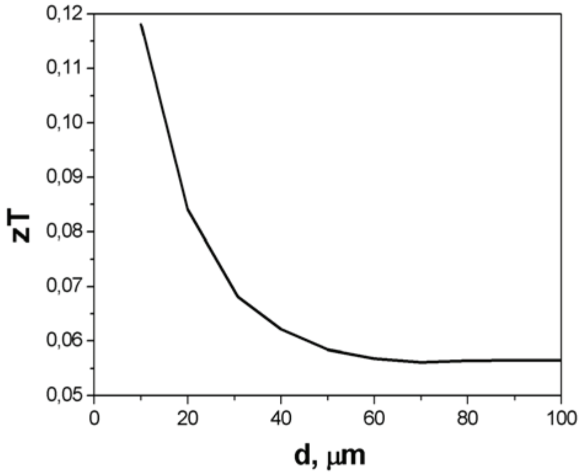

Fig. 6. ZT parameter versus diameter in $Si_{1-x}Ge_x$ (x = 0.03) whiskers (T = 300 K, n = $1{\cdot}10^{19}$ cm^{-3})

Taking into account the obtained parameters one can calculate ZT value for the whiskers. The dimensional dependence of ZT for $Si_{1-x}Ge_x$ (x = 0.03) whiskers with hole concentration p = $1{\cdot}10^{19}$ cm^{-3} at T = 300 K is presented at Fig.6.

As you can see from Fig. 6, a significant rise of ZT occurs at decrease of the whisker diameter down 20 μm. This fact is promising for further increase of the whisker figure-of-merit when diameter becomes of about nanometer scale.

Conclusions

The manuscript presents a study of influence of $Si_{1-x}Ge_x$ (x = 0.03) whisker geometry on their thermoelectric parameters. The whiskers have the diameters ranged from 10 to 100 μm, besides the whiskers with obligaty $\Delta d/2\Delta l$ of about $(1.5\text{-}3.0)\cdot10^{-3}$ have been investigated. The obtained results have shown that the whisker resistance and Seebeck coefficient increases when their diameters drops. The calculation of the distribution component of the heat flux along the whiskers has shown that thermal conductivity decreases with the diameter drop. The obtained results allow us to calculate a figure-of-merit, that for thin (of about 10μm) whiskers with high boron concentration $1{\cdot}10^{19}$ cm^{-3} approaches to 0.12 at room temperature. The value is rather high for Si-Ge solid solution: on one side, one can approach ZT almost to 1.0 in the high temperature range (900-100 K); on another side, one can suppose substantial growth of the whisker figure-of-merit using the nanoscale whisker diameters.

References

1. Vining C. A model for the high-temperature transport properties of heavily doped n-type silicon-germanium alloys // J. Appl. Phys. – 1991. – Vol. 69, No. 1. – P. 331–341.
2. Ioffe A.V., Ioffe A.F. Influence of impurities on thermal conductivity of semiconductors // Doklady Akademii Nauk SSSR. – 1954. – Vol. 8, No. 5. – P. 757-759, in Russian.
3. Slack G., Hussain M. The Maximum Possible Conversion Efficiency of Silicon-Germanium Thermoelectric Generators // J.Appl.Phys. – 1991. – Vol. 70, No. 5. – P. 2694-2718.
4. Thermal conductivity of individual silicon nanowires / D. Li, Y. Wu, P. Kim, et al. // Appl. Phys. Lett. – 2003. – Vol. 83, No. 14. – P. 2934-2936.
5. Thermal conductance of thin silicon nanowires / R.Chen, A.I. Hochbaum, P. Murphy, et al. // Phys. Rev. Lett. – 2008. – Vol. 101. – P. 105501-1 - 105501-4.
6. Quantifying Surface Roughness Effects on Phonon Transport in Silicon Nanowires / J. Lim, K. Hippalgaonkar, S. Andrews, et al. // Nano Lett. – 2012. – Vol. 12. – P. 2475-2482.
7. Holey Silicon as an Efficient Thermoelectric Material / J. Tang, H. Wang, D.H. Lee, et al. // Nano Lett. – 2010. – Vol. 10. – P. 4279-4283.

8. Atomic-Level Control of the Thermoelectric Properties in Polytypoid Nanowires / S.C. Andrews, M.A. Fardy, M.C. Moore, et al. // Chem. Sci. – 2011. – Vol. 2. – P. 706-711.
9. Maycock P. Thermal Conductivity of Silicon, Germanium, III-V Compounds and III-V Alloys // Solid-State Electron. – 1967. – Vol. 10. – P. 161-168.
10. Steele M., Rosi F. Thermal Conductivity and Thermoelectric Power of Germanium-Silicon Alloys // J. Appl. Phys. – 1958. – Vol. 29, No. 11. – P. 1517-1520.
11. Meddins H., Parrott J. The Thermal and Thermoelectric Properties of Sintered Germanium-Silicon Alloys // J. Phys. C: Solid State Phys. – 1976. – Vol. 9. – P. 1263-1276.
12. Bhandari C. CRC Handbook of Thermoelectrics, ch. Minimizing the Thermal Conductivity (CRC Press, Inc.).– 1994.– P. 55-65.
13. Strasser M. Miniaturized Thermoelectric Generators based on poly-Si and poly-SiGe surface Micromachining // Sensors and Actuators A: Physical. – 2002. – Vol. 97-98. – P. 535-542.
14. Wang Z., Mingo N. Diameter Dependence of SiGe Nanowire Thermal Conductivity // Appl. Phys. Lett. – 2010. – Vol. 97. – P. 101903-101907.
15. Lee E. K. Large Thermoelectric Figure-of-Merits from SiGe Nanowires by Simultaneously Measuring Electrical and Thermal Transport Properties // Nano Lett. – 2012. – Vol. 12. – P. 2918-2923.
16. Cluster expansion and optimization of thermal conductivity in SiGe nanowires / M.K.Y. Chan, J. Reed, D. Donadio, et al. // Phys. Rev. B. – 2010. – Vol. 81. – P. 174303-174307.
17. Upadhyaya M., Aksamija Z. Phonon Transport in SiGe-Based Nanocomposites and Nanowires for Thermoelectric Applications // Mater. Res. Soc. Symp. Proc. – 2015. – Vol. 1735.
18. B. Xu, C. Li, M. Myronov, K. Fobelets, "n-Si-p-$Si_{1-x}Ge_x$ nanowire arrays for thermoelectric power generation," Solid State Electron. – 2013. – Vol. 83. – P. 107-112.
19. Thermoelectric Performance of $Si_{0.8}Ge_{0.2}$ Nanowire Arrays / B. Xu, C. Li, K. Thielemans, et al. // EE T. Electron. Dev. – 2012. – Vol. 59, No. 12. – P. 3193-3198.
20. Thermo-EMF in Si-Ge solid solution whiskers / A.A. Druzhinin, I.P. Ostrovskii, N.S. Liakh, and S.M. Matvienko // Journal of Physical Studies. – 2005. – Vol. 9, No. 1. – P. 71-74, in Ukrainian.
21. Druzhinin A., Ostrovskii I., Kogut I. Thermoelectric properties of Si-Ge whiskers // Materials Science in Semiconductor Processing. – 2006. – Vol. 9. – P. 853-857.
22. Si and Si-Ge wires for thermoelectrics / A. Druzhinin, I. Ostrovskii, I. Kogut, et al. // Phys. Stat. Sol. C. – 2011. – Vol. 8, No. 3. – P. 867-870.
23. Low temperature characteristics of germanium whiskers / A.A. Druzhinin, I.P. Ostrovskii, Yu.N. Khoverko, et al. // Functional Materials. – 2014. – Vol. 21, No. 2. – P. 130-136.
24. Strain effect on magnetoresistance of SiGe solid solution whiskers at low temperatures / A.A. Druzhinin, I.P. Ostrovskii, Yu.M. Khoverko, et al. // Materials Science in Semiconductor Processing. – 2011. – Vol. 14, No 1. – P. 18-22.
25. Druzhinin A.A., Ostrovskii I.P. Investigation of Si-Ge whiskers growth by CVD // Phys. Stat. Sol. C. – 2011. – Vol. 2. – P., vol. 1, No. 2, pp. 333-336, 2004.
26. Low temperature semiconductor mechanical sensors / I. Maryamova, A. Druzhinin, E. Lavitska, et al. // Sensors and Actuators. – 2000. – Vol. A85. – P. 153-157.
27. Druzhinin A., Ostrovskii I., Liakh N. Study of piezoresistance in Ge_xSi_{1-x} whiskers for sensor application // Materials Science in Semiconductor Processing. – 20005. – Vol. 8, No. 1-3. – P. 193-196.
28. Technological approaches for growth of silicon nanowire arrays / A. Druzhinin, A. Evtukh, I. Ostrovskii, et al. // Springer Proceedings in Physics. – 2015. – Vol. 156. – P. 301-308.
29. Measurement of thermal conductivity of individual multiwalled carbon nanotubes by the 3-ω method / Tae Y. Choi, Dimos Poulikakos, Joy Tharian, Urs Sennhauser // Appl. Phys. Lett. – 2005. – Vol. 87. – P. 013108-1–013108-4.
30. Thermoelectric properties of oblique SiGe whiskers / A. Druzhinin, I. Ostrovskii, N. Liakh-Kaguy, Iu. Kogut // Journal of Nano- and Electronic Physics. – 2016. – Vol. 8, No. 2. – P. 02030-1–02030-5.
31. H. Böttner. Thermoelectric Micro Devices: Current State, Recent Developments and Future Aspects for Technological Progress and Applications: http://www.micropelt.com/down/ict02_haboe.pdf. (2002).

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Термоелектричні властивості ниткоподібних кристалів SiGe

Проблематика. Ниткоподібні кристали твердого розчину $Si_{1-x}Ge_x$ з низьким вмістом германію мають максимальне відношення рухливості до фононної теплопровідності, що перспективно для термоелектрики. Теплопровідність нанодротів SiGe є нижчою, ніж об'ємних зразків, що є також перспективним для покращення термоелектричної добротності та розвитку високоефективних термоелектричних мікроконвертерів. Вивчено температурну поведінку коефіцієнта Зеєбека ниткоподібних кристалів твердого розчину $Si_{1-x}Ge_x$ в діапазоні температур від 4,2 К до температур вище кімнатної. Особливості ниткоподібних кристалів, зумовлені їх геометрією успішно використовуються для визначення термоелектричних параметрів кристалів, однак такі дослідження не проводились для ниткоподібних кристалів твердого розчину SiGe.

Мета досліджень. Вивчення можливого впливу геометрії ниткоподібних кристалів $Si_{1-x}Ge_x$ на їх термоелектричні параметри.

Методика реалізації. Ниткоподібні кристали SiGe вирощували методом хімічного осадження в закритій бромідній системі. 3ω метод було використано для визначення температурної залежності теплопровідності ниткоподібних кристалів $Si_{1-x}Ge_x$ (x = 0,01-0,05) в інтервалі температур 300-400 К. Опір кристалів вимірювали двохзондовим методом. Отримані вольт-амперні характеристики хрестоподібних зростків були використані для визначення типу провідності матеріалу кристалів.

Результати досліджень. Для НК SiGe діаметром від 100 до 10 mµ із зменшенням їх теплопровідності спостерігається збільшення коефіцієнта Зеєбека та опору, що супроводжується підвищенням показника якості (до 0,12 за температури 300 К). Використання ниткоподібних кристалів з великою конусністю, призводить до невеликого підвищення їх коефіцієнта Зеєбека (близько 10-15%).

Висновки. Досліджено термоелектричні властивості ниткоподібних кристалів твердого розчину $Si_{1-x}Ge_x$ (x = 0,03), легованих домішкою бору з концентрацією $1\cdot10^{17}–1\cdot10^{19}$ см$^{-3}$ в інтервалі температур 300-420 К. Встановлено вплив морфології ниткоподібних кристалів, зокрема, їх діаметрів і геометрії, на коефіцієнт Зеєбека, теплопровідність та опір.

Ключові слова: SiGe; ниткоподібні кристали; термоелектричні властивості; коефіцієнт Зеєбека; теплопровідність.

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Термоэлектрические свойства нитевидных кристаллов SiGe

Проблематика. Нитевидные кристаллы твердого раствора $Si_{1-x}Ge_x$ с низким содержанием германия имеют максимальное отношение подвижности к фононной теплопроводности, что перспективно для термоэлектричества. Теплопроводность нанопроводов SiGe ниже, чем объемных образцов, что является также перспективным для улучшения термоэлектрической добротности и развития высокоэффективных термоэлектрических микроконвертеров. Изучено температурную поведение коэффициента Зеебека нитевидных кристаллов твердого раствора $Si_{1-x}Ge_x$ в диапазоне температур от 4,2 К до температур выше комнатной. Особенности нитевидных кристаллов, обусловленные их геометрией успешно используются для определения термоэлектрических параметров кристаллов, однако такие исследования не проводились для нитевидных кристаллов твердо-го раствора SiGe.

Цель исследований. Изучение возможного влияния геометрии нитевидных кристаллов $Si_{1-x}Ge_x$ на их термоэлектрические параметры.

Методика реализации. Нитевидные кристаллы SiGe выращивали методом химического осаждения в закрытой бромидной системе. 3ω метод был использован для определения температурной зависимости теплопроводности нитевидных кристаллов $Si_{1-x}Ge_x$ (x = 0,01-0,05) в интервале температур 300-400 К. Сопротивление кристаллов измеряли двухзондовим методом. Полученные вольт-амперные характеристики крестообразных сростков были использованы для определения типа проводимости материала кристаллов.

Результаты исследований. Для НК SiGe диаметром от 100 до 10 µm с уменьшением их теплопроводности наблюдается увеличение коэффициента Зеебека и сопротивления, что сопровождается повышением показателя качества (до 0,12 при температуре 300 К). Использование нитевидных кристаллов с большой конусностью, приводит к небольшому повышению их коэффициента Зеебека (около 10-15%).

Выводы. Исследованы термоэлектрические свойства нитевидных кристаллов твердого раствора (x = 0,03), легированных примесью бора с концентрацией $1\cdot10^{17}–1\cdot10^{19}$ см$^{-3}$ в интервале температур 300-420 К. Установлено влияние морфологии нитевидных кристаллов, в частности, их диаметров и геометрии, на коэффициент Зеебека, теплопроводность и сопротивление.

Ключевые слова: SiGe; нитевидные кристаллы; термоэлектрические свойства; коэффициент Зеебека; теплопроводность.