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SHORT COMMUNICATION

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About the electrical conductivity of p-SixGe1-x

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ABSTRACT

The specific, reduced and universal electrical conductivities of silicon/germanium is studied in this paper. Si_xGe_{1-x} samples with different compositions were used for research: x=0.7, 0.76 and 0.8. Their conductivity is p-type, for which they were doped with boron. The temperature dependences of reduced electrical conductivity for individual samples have the shape of a "distorted" inverted parabola i.e., they are characterized by a maximum. Based on these maximum values of reduced electrical conductivity, the maximum values of the figure of merit ($ZT=\sigma S^2T/k$, σ – specific electrical conductivity, S – Seebeck coefficient, T – absolute temperature and k – total thermal conductivity) of the samples can be determined. $(ZT)_{max}$ can also be defined by σ'min. The Seebeck coefficient and the natural logarithm of the specific electrical conductivity are mutually proportional. Our data shows that for all three samples under study, the experimental points forms almost the single set. From this dependence you can obtain information about such important characteristics as the scattering parameter, effective mass and mobility of charge carriers.

KEY WORDS

Silicon-germanium; Doped with boron; Electrical conductivity; Reduced and universal electrical conductivities; Figure of merit

ARTICLE HISTORY

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Introduction

The most important characteristics of any material - specific electrical conductivity, the reciprocal of specific electrical resistance, is related to the cell constant (electrochemistry), to the molar electrical conductivity, and to the characteristics of charge carriers. Of course, this is also of crucial importance in micro- and nanoelectronics.

This paper studies the specific, reduced and universal electrical conductivities of silicon-germanium (SiGe). Due to its higher electron and hole mobility compared to silicon, SiGe films are used in microelectronics to create high-speed integrated circuits (which is critical for mobile communications, Wi-Fi, and radar), heterojunction transistors, infrared sensors, and photovoltaic converters [1-7]. SiGe-based materials are also used as elements that convert thermal energy into electrical energy, especially in high-temperature applications. In particular, SiGe is a key element in spacecraft generators [8,9].

The concepts introduced into the theory – reduced and universal conductivity – are also discussed. The dependence of the maximum figure of merit on these last two parameters is established.

Materials and Methods

Si_xGe_{1-x} (x=0.7, 0.76, and 0.8) films were obtained by vacuum evaporation of the powder, prepared according to the method described in [10,11]. SiGe powders were produced by vacuum hot pressing and obtained from zone-melting ingots. Bulk Si and Ge waste materials were crushed with a steel rod and sifted through a sieve with 0.2 mm cells. Then it was loaded into the mill chamber REK PM-100 SM and crushed for 20-25 hours. The granulometric composition of the powder was estimated using a Nikon optical microscope and a DRON-3M X-ray diffractometer. The dispersed SiGe alloy powder obtained in this mode consisted of grains of constituent elements with sizes of 60-80 nm. The resulting powder was pressed in a high-temperature vacuum induction pressure chamber at temperatures of (1200-1320) °C and a pressure of 480 kg·cm-2 for (20-30) minutes. The matrix and punches were made of high-strength graphite. Profiled samples in the form of rectangular parallelepipeds measuring 10 x 10 x 20 mm were cut out from the obtained briquettes on a diamond-disc cutting device. Boron was used as a dopant, providing p-type conductivity in a large number of materials [12-15]. The initial concentration of charge carriers was $3.2\cdot10^{26}m^{-3}$.

Results and Discussion

Figure 1 shows the temperature dependences of the specific electrical conductivity of the studied samples.

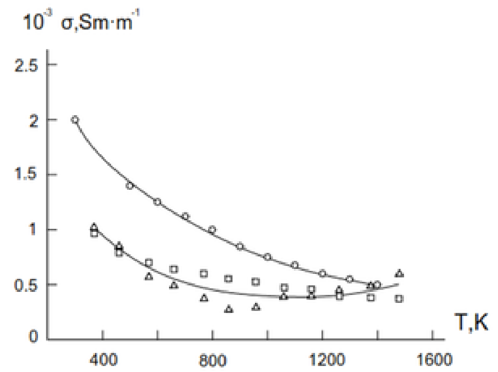

Figure 1. σ – T dependences for Si_xGe_{1-x} : x=0.7 (o), 0.76 (Δ) and 0.8 (□).

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The specific electrical conductivity of semiconductor films typically ranges from 10^{-2} to 10^{12} $Sm{\cdot}m^{-1}$. Therefore, our obtained values can be considered average. Such electrical conductivity in semiconductor structures is a parameter that strongly depends on production technology, temperature, and doping level. It often differs from the bulk conductivity of the material due to size effects and the influence of interfaces. Films with medium electrical conductivity are widely used in applications where conductivity is required but the high conductivity characteristic of metals is not. They are used in microelectronics, sensors and detectors, optics (e.g., interference coatings), radio frequency technology, and other applications.

Figure 1 shows that, over the entire temperature range studied, the σ values for $Si_{0.76}Ge_{0.24}$ and $Si_{0.8}Ge_{0.2}$ are close to each other but differ from those for $Si_{0.7}Ge_{0.3}$. And for σ', these dependences form practically single area (see below). However, it should be noted that even if the temperature dependences of σ were significantly different, the points of σ' would still form a uniform grid. The reason for this is the fact that the electronic quality factor B_E, which enters into the expression of σ', scales σ.

Now let us consider the reduced and universal electrical conductivity, which we will denote by σ″ and σ', respectively:[1]

$$\sigma'' = (k_B/q_e)^2 T\sigma/k_L \cong 7.425 \cdot 10^{-9}\, T\sigma/k_L \qquad (1)$$

(k_B – Boltzmann's constant, q_e – elementary charge, k_L – lattice thermal conductivity) [16] and

$$\sigma' = \sigma(q_e/k_B)^2/B_E \cong 1.347 \cdot 10^{8}\sigma/B_E \qquad (2)$$

where $B_E = \sigma S^2/B_S$ is electronic quality factor,

$$B_S = \left[\frac{S_r^2 e^{2-S_r}}{1+e^{-5(S_r-1)}} + \frac{\frac{\pi^2}{3}S_r}{1+e^{5(S_r-1)}}\right]$$

is the scaled power factor and $S_r = (q_e/k_B)\,|S|$ is reduced Seebeck coefficient [17]. The temperature dependences of the first of these parameters for SixGe1-x is shown in Figure 2. They have the shape of a "distorted" inverted parabola i.e., they are characterized by a maximum. Based on these maximum values of reduced electrical conductivity, the maximum values of the figure of merit of the samples are determined (Figure 3).

From the above formulas it follows that $\sigma' = \sigma(q_e/k_B)^4 B_S/S_r^2$, i.e. the universal electrical conductivity can be determined using only the reduced Seebeck coefficient (in fact, the Seebeck coefficient).

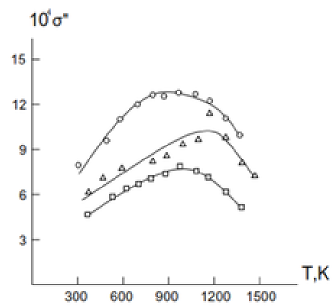

Figure 2. σ″– dependences for Si_xGe_{1-x} : x=0.7 (o), 0.76 (Δ) and 0.8 (□).

Figure 4 shows the temperature dependences of universal electrical conductivity. As with reduced conductivity, universal conductivity can also be used to determine the maximum figure of merit of samples Figure 3.

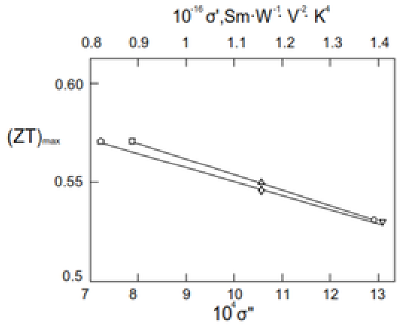

Figure 3. Dependence $(ZT)_{max}$ – σ″ and $(ZT)_{max}$– σ' for Si_xGe_{1-x}: x=0.7 (o, ∇) , 0.76 (Δ, ◊) and 0.8 (□, ⌂).

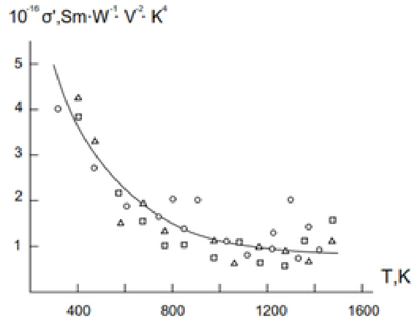

Figure 4. σ' – T dependences for Si_xGe_{1-x}: x=0.7 (o), 0.76 (Δ) and 0.8 (□).

According to the literature, the Seebeck coefficient and the natural logarithm of the specific electrical conductivity are mutually proportional [18-20]. Rowe and Min shows S – lnσ dependences for various thermoelectric materials (PbTe, Bi_2Te_3, LaS, etc.), including SiGe. All of them are rectilinear. Our data shows that for all three samples under study, the experimental points form almost a single set in Figure 5. From this dependence, you can obtain information about such important characteristics as the scattering parameter, effective mass, and mobility of charge carriers. We are going to present these data in the next publication.

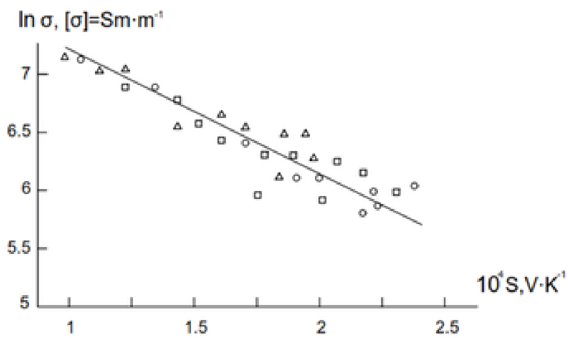

Figure 5. lnσ – S dependences for Si_xGe_{1-x} : x=0.(o), 0.76 (Δ) and 0.8 (□).

[1]The correlation between σ″ and σ' governs how a band structure and carrier concentrations impact maximum performance potential. As will be shown below, these parameters can be used to determine the maximum value of the figure of merit.

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Conclusion

The specific, reduced, and universal electrical conductivities of p-type silicon/germanium were studied in the paper. SixGe1-x samples with different compositions were used for research: x=0.7, 0.76, and 0.8. Their conductivity is p-type, for which they were doped with boron. The temperature dependence of universal electric conductivity forms unified network. The temperature dependence of reduced electrical conductivity for individual samples is characterized by a maximum. Based on these maximum values of reduced electrical conductivity, the maximum values of the figure of merit of the samples are determined. The dependence of the natural logarithm of specific electrical conductivity on the Seebeck coefficient was also studied. For all three samples, the experimental data points form a virtually uniform set. This dependence can be used to obtain information about important material characteristics.

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Disclosure Statement

No potential conflict of interest was reported by the author.

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