

## Elements of the fifth group (semimetals) and their alloys — are they the new high-temperature super-conductors?

*Yu.I.Boyko*<sup>1</sup>, *V.V.Bogdanov*<sup>1</sup>, *R.V.Vovk*<sup>1</sup>, *B.V.Grinyov*<sup>2</sup>

<sup>1</sup>V.Karazin Kharkiv National University, 4 Svobody Sq., 61022 Kharkiv, Ukraine

<sup>2</sup>Institute for Scintillation Materials, STC "Institute for Single Crystals",  
National Academy of Sciences of Ukraine,  
60 Nauky Ave., 61072 Kharkiv, Ukraine

*Received June 25, 2020*

Based on the BCS (Bardeen, Cooper, Schrieffer) microscopic quantum theory of superconductivity, an analysis of the electrical conductivity of the elements of fifth group of the periodic system (semimetals) under external pressure is performed. It is shown that, under the action of a pressure  $P \approx 10^7$  Pa, semimetals can transform into metals characterized by a specific energy spectrum of electrons. A change in the structure of semimetals and in the parameters of the energy spectrum of the electronic subsystem is accompanied by an increase in the electron pairing constant and the density of electronic states at the Fermi level. In turn, an increase in these parameters makes it possible to transfer semimetals to the superconducting state at a temperature of  $\approx 300$  K.

**Keywords:** High-Temperature Superconductivity (HTSC), semimetals, percolation effect.

**Елементи п'ятої групи (напівметали) і їх сплави — нові високотемпературні надпровідники?** *Ю.І.Бойко, В.В.Богданов, Р.В.Вовк, Б.В.Гриньов*

На підставі мікроскопічної квантової теорії надпровідності BCS (Bardeen, Cooper, Schrieffer) проведено аналіз електричної провідності елементів п'ятої групи періодичної системи (напівметалів) в умовах дії зовнішнього тиску. Показано, що під дією тиску  $P \approx 10^7$  Па напівметали можуть перетворюватися на метали, які характеризуються специфічним енергетичним спектром електронів. Зміна структури і параметрів енергетичного спектра електронної підсистеми напівметалів супроводжується збільшенням константи спарювання електронів і щільності електронних станів на рівні Фермі. У свою чергу, збільшення зазначених параметрів обумовлює можливість переходу напівметалів у надпровідний стан при температурі  $\approx 300$  К.

На основании микроскопической квантовой теории сверхпроводимости BCS (Bardeen, Cooper, Schrieffer) проведен анализ электрической проводимости элементов пятой группы периодической системы (полуметаллов) в условиях действия внешнего давления. Показано, что под действием давления  $P \approx 10^7$  Па полуметаллы могут превращаться в металлы, характеризующиеся специфическим энергетическим спектром электронов. Изменение структуры и параметров энергетического спектра электронной подсистемы полуметаллов сопровождается увеличением константы спаривания электронов и плотности электронных состояний на уровне Ферми. В свою очередь, увеличение указанных параметров обуславливает возможность перехода полуметаллов в сверхпроводящее состояние при температуре  $\approx 300$  К.

## 1. Introduction

Since 1911, when the electrical superconductivity of frozen mercury (Hg) in liquid helium was discovered at a temperature  $T_c \approx 4.2$  K, researchers discovered a large number of other elements, binary or ternary alloys, and more complex compounds with this unique property. Herewith, the main disadvantage of all these materials was that they transferred to the superconducting state at very low temperatures  $\approx (10-40)$  K. This fact significantly limited their use in practice. In this connection, the problem arose of searching for materials with superconductivity at higher temperatures. Moreover, in order to use superconductors for technical purposes, it is desirable that the critical temperature  $T_c$  reaches room temperature ( $\approx 300$  K). However, despite the fact that in 1957 a microscopic theory of superconductivity was developed (BCS theory [1]), the list of new superconductors for a long time remained very small, and their critical transition temperature  $T_c$  remained low.

A significant and well-known breakthrough in the search for new superconducting materials was the discovery in 1986-1988 of the so-called "high-temperature" superconductors. These are metal oxides with superconductivity at temperatures above the boiling point of liquid nitrogen ( $T_c = 77.3$  K) — an inexpensive and procurable refrigerant [2-7]. However, despite the importance of this discovery, the highest value of the critical temperature  $T_c$  of the metal oxides was  $\approx 164$  K, which is significantly less than the desired value 300 K.

The next important step in the search for materials with a higher transition temperature  $T_c$  was the discovery of superconductivity of hydrogen compounds (hydrides) [8, 9]. In essence, these works opened up a new direction in the study of the superconductivity phenomenon. It was found that the  $H_3S$  compound becomes a superconductor at the temperature  $T_c \approx 203$  K. Note, that the possibility of a transition to the superconducting state of hydrogen compounds at elevated temperatures was predicted much earlier than the first experimental evidence of this fact appeared [10]. This assumption was based on the following considerations. Compounds containing hydrogen atoms should be close in their properties to metallic hydrogen. In fact, metallic hydrogen, due to its small mass and size of atoms, should have a phonon spectrum with an increased fraction of high-frequency phonons

and, as a consequence, should be characterized by a strong electron-phonon interaction. It is this nature of the interaction of electrons, in accordance with the BCS theory, that determines the formation of specific charge carriers — bosons (pairs of electrons) moving in superconductors without resistance. Following to this logic, an idea arose that compounds of hydrogen with other atoms that easily generate electrons can also be superconductors like metallic hydrogen. However, at atmospheric pressure, solid hydrogen is a molecular dielectric, and metallic hydrogen, which by all indications should be a superconductor, exists only at very high pressure  $\geq 10^4$  GPa. Such a high level of pressure is necessary for the implementation of the "collectivization" process of valence electrons, that is, for the formation of a "gas of degenerate electrons" (Fermi gas) in the material.

According to [10], hydrogen compounds with some metals should also have superconductivity under pressure, however, at a lower value than is necessary for the existence of metallic hydrogen. The correctness of this idea was confirmed experimentally in [8, 9], as well as in subsequent studies (see, for example, [11-13]). It was found that hydrogen sulfide  $H_3S$ , as well as other hydrogen compounds (for example,  $LaH_{10}$ ), also become superconducting at relatively high temperatures  $\approx (200-250)$  K. Herewith, the superconductivity of these materials in the indicated temperature range is appear only at a pressure of  $P \approx 150$  GPa.

Thus, despite the fact that the temperature of transition of hydrogen compounds to the superconducting state is close enough to room temperature, the need to use a sufficiently high pressure has not removed the restrictions on the use of these superconductors for technical purposes. Therefore, a new problem has become urgent: the synthesis of such a material that would have a transition temperature  $T_c$  close to room temperature, as in hydrides, but its superconductivity would be realized under the action of a much lower pressure. This paper discusses the possible chemical composition of the material, which, in our opinion, can satisfy the specified requirement.

We emphasize that in our consideration, we use the main conclusion of the microscopic theory of superconductivity BCS, according to which superconductivity is due to electron-phonon interaction [1]. Other mechanisms of the formation of paired electrons, the manifestation of which is associ-

ated with various kinds of electronic excitations — excitons, plasmons, spin fluctuations, etc. — have not been unambiguously confirmed; therefore their possible role is not considered.

## 2. Analysis of possible ways to increase the critical transition temperature $T_c$

According to the BCS theory, the temperature of transition to the superconducting state as a result of electron-phonon interaction is described by the following relation:

$$T_c \approx \Theta \exp[-(1+\lambda)/(\lambda - \mu)]. \quad (1)$$

Here  $\Theta = (h\nu_m)/k$  is the characteristic temperature (Debye temperature), determined by the maximum vibrational frequency of atoms (phonons);  $h$  is the Planck constant;  $k$  is the Boltzmann constant;  $\nu_m$  is the maximum frequency of the phonon spectrum;  $\lambda$  is the electron pairing constant ( $\lambda \leq 1$ );  $\mu$  is the so-called Coulomb pseudopotential characterizing the mutual repulsion of electrons (usually  $\mu \approx 0.1$ ).

In the case of weak pairing of electrons, i.e., at  $\lambda \ll 1$  and neglecting the mutual repulsion of electrons, i.e., under the condition  $\mu \approx 0$ , equation (1) is transformed to

$$T_c \approx \Theta \exp(-1/\lambda). \quad (2)$$

For many metals and superconducting compounds, the Debye temperature is in the interval of values  $\Theta \approx (100-300)$  K. In accordance with (2), for the pairing constant  $\lambda_0 \approx 0.3$ , the critical temperature of the transition to the superconducting state of these materials is characterized by  $T_c \approx (5-40)$  K, which is in good agreement with experimental data.

From relations (1) and (2) it follows that when choosing the chemical composition of a superconducting compound with a higher value of  $T_c$ , the following circumstances must be taken into account. Firstly, it is important that the desired material has a high Debye temperature  $\Theta$ . Since  $\nu_m \sim 1/M^{1/2}$  ( $M$  is the mass of the atoms that generate phonons) and  $\nu_m \approx 1/2R$  ( $R$  is the distance between nearest neighboring atoms), it is desirable that the superconductor material consists of atoms with a lower mass  $M$  and that they are located in the crystal lattice as close to each other as possible. The effectiveness of this method for

synthesizing superconducting materials with an increased transition temperature  $T_c$  is confirmed by the discovery of superconductivity in hydrogen compounds. However, as it already indicated, the superconductivity of hydrogen compounds is realized only at a very high pressure, which is necessary for the "metallization" of these materials, as well as for the special structural state of the formation of materials [14].

Another possible way to increase the critical transition temperature  $T_c$  is to increase the electron pairing constant  $\lambda$ . Indeed, as follows from theoretical estimations, in the case of strong pairing, i.e., when the condition  $\lambda \gg 1$  is satisfied, relations (1) and (2) are not applicable, and the dependence  $T_c = f(\lambda)$  is described by the different relation [15]:

$$T_c \approx 0.2\lambda^{1/2}\Theta. \quad (3)$$

Obviously, in this case, an increase in the pairing constant  $\lambda$  can cause an increase in the transition temperature  $T_c$ . One of the possibilities of increasing the pairing constant is to use its dependence on the characteristic value of the density of energy states of electrons  $n_s^*$

$$\lambda \approx Un_s^*. \quad (4)$$

Here  $n_s^*$  is the density of states in a narrow energy range  $\Delta E$  (energy gap) directly near the Fermi energy level  $E_F$  ( $E_F$  is the maximal energy of a system of  $N$  electrons at  $T = 0$ ),  $U$  is the potential characterizing the electron-lattice interaction.

In the general case, the density of states  $n_s$  characterizes the change in the number of electrons per unit energy interval,  $n_s = dN/dE$  (it is assumed that the total number of states is determined by the number of electrons  $N$ ). To calculate the desired characteristic density of states  $n_s^*$  we use the formula that describes the actual value  $E_F$ ,

$$E_F = (3/4\pi)^{2/3}(h^2/2m)(N/V)^{2/3}. \quad (5)$$

Here  $h$  is the Planck's constant;  $m$  is the electron mass;  $V$  is the material volume.

From relation (5) it follows that

$$N = \text{const} \cdot (E_F)^{3/2}.$$

Accordingly,  $\ln N \approx (3/2)\ln E_F$  and, consequently,  $dN/N \approx (3/2)(dE_F/E_F)$ . Therefore, the density of states  $n_s$  for  $E \leq E_F$  can be described by the simple formula:

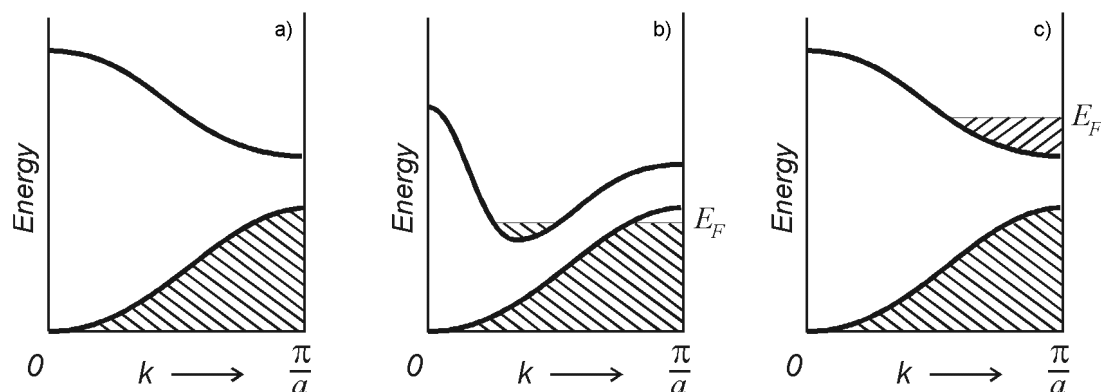


Fig. 1. Occupied states (shaded areas) in various zone energy structures: a) insulator, b) semimetal, c) metal.

$$n_s \approx \frac{3}{2} \frac{N}{E_F}. \quad (6)$$

Here  $N$  is the number of electrons in the conduction zone with energy  $E \leq E_F$ .

It should be noted that in (4) the density of states  $n_s^*$  characterizes energy states in the narrow energy range  $\Delta E \approx 10^{-4} E_F$ , directly at the Fermi level. This is due to the fact that, in accordance with BCS theory, the formation of electron pairs providing electrical superconductivity occurs when only those electrons interact, the energy states of which correspond to a specified energy gap. Only this insignificant part of conduction electrons is involved in the process of their pairing. Therefore, in our consideration, the value of  $N$  in relation (6) must be replaced by  $N^*$ , where  $N^* \ll N$  and characterizes the number of electrons, the energy of which corresponds to the energy interval  $\Delta E$  located directly near the Fermi level. The value of  $N^*$  can be considered approximately the same for all materials with electrical superconductivity.

In ordinary metals, which are good conductors, the number of conduction electrons  $N$  is in the order of magnitude equal to the number of atoms  $N \approx N_{at} \approx 10^{29} \text{ m}^{-3}$ . Accordingly, for most metals the Fermi energy is about (5–10) eV (see (5)); and the level  $E = E_F$  is in the conduction zone (Fig. 1c). Herewith, such metals as Cu, Au, and Ag generally do not have superconductivity, and for Al this property appear only at very low temperature  $\approx 1 \text{ K}$ . In accordance with the above analysis, this can be explained by the fact that these metals are characterized by high Fermi energy and, accordingly, have very small values of the parameters  $n_s^*$  and  $\lambda$  (see (2)–(6)).

Summarizing the above considerations, we can draw the following conclusion. To synthesize a superconducting material having a higher transition temperature  $T_c$ , the following requirements must be met. First, the electronic subsystem of material must be a system of "degenerate" electrons, that is, quantum particles obeying the Fermi-Dirac statistics. Secondly, the electronic subsystem of the synthesized material must have a relatively low Fermi energy and, accordingly, a high value of the pairing constant  $\lambda$  (see (2), (4) and (6)). Thirdly, in addition to the above two conditions, for the existence of a superconducting state at higher temperatures, a phonon spectrum with a significant fraction of high-frequency phonons should form in the material (see (1)–(3)). Materials that, in our opinion, can satisfy all three of these conditions are metals of the fifth group of the periodic system of elements (semimetals), as well as solid solutions based on them.

The following paragraph of this work is devoted to the consideration of the electrical properties of these materials, as well as to the discussion of conditions (temperature and pressure) for their superconductivity.

### 3. Conditions for the realization of "high-temperature" superconductivity in materials based on elements of the fifth group

The following materials belong to the fifth group of the periodic system of elements: Bi, Sb, As and etc. [16]. We consider in more detail two elements: bismuth (Bi) and antimony (Sb). Under ordinary conditions (at atmospheric pressure and room temperature), the atoms of these substances

are characterized by the electronic configuration  $s^2p^3$ , and the resulting crystalline phase in its electrical properties occupies an intermediate position between metals and semiconductors. Therefore, these substances are called semimetals. They are characterized by a slight overlap of the valence and conduction zones (see Fig. 1,b). On the one hand, semimetals are good conductors of electricity, and on the other hand, they have a much lower density of charge carriers compared to ordinary metals. For example, at room temperature the density of conduction electrons ( $N/V$ ) is about  $10^{24} \text{ m}^{-3}$  in bismuth and near  $10^{25} \text{ m}^{-3}$  in antimony. Unlike ordinary metals, the electrical conductivity of these substances increases with increasing temperature. These features of the electrical properties of semimetals make them similar to the so-called "non-degenerate" semiconductors [17]. However, under pressure, the semimetals can be "metallized" that is, they change the overlap of the energy zones and, accordingly, change the nature of the filling of energy levels with electrons. As a result of these changes, semimetals can become similar to ordinary metals in the structure of the energy spectrum of electrons. However, in this case, their electrical properties should differ significantly from the electrical properties of metals. In particular, semimetals and their solutions may have superconductivity under pressure. This statement is based on the following considerations and estimates.

The magnitude of the pressure  $P$ , under the action of which the transformation of any solid substance (dielectric, semiconductor, semimetal) into metal can be realized, is described by the following relation:

$$P \approx 0.1(h^2/mr^2)(N/V). \quad (7)$$

Here  $r$  is the radius of the potential "well" characterizing the localization of electrons in atoms before the solid phase formation; ( $N/V$ ) is the density of "collectivizable" electrons (before their transition from the "non-degenerate" to the "degenerate" state, inherent in all metals) [17]. For a multi-electron atom,  $r$  is the radius of the orbit of the electron farthest from the nucleus. Specifically for Bi atoms,  $r = 1.8 \cdot 10^{-10} \text{ m}$ ; for Sb atoms,  $r = 1.6 \cdot 10^{-10} \text{ m}$  [16]. Substituting in (7) the numerical values of  $h$ ,  $m$ ,  $r$  and ( $N/V$ ) for Bi and Sb we obtain, respectively:  $P \approx 10^6 \text{ Pa}$  and  $P \approx 10^7 \text{ Pa}$ . This pressure level is much less than the pressure that ensures the "metallization" of hy-

drogen compounds and their superconductivity (see section 1).

According to the estimate made, a pressure of  $\approx 10^7 \text{ Pa}$  can cause the transformation of semi-metal into metal, which, however, must have special electrical properties. One of this specific properties of a metal obtained from a semimetal under pressure can be an increase in the values of the parameters  $n_s^*$  and  $\lambda$ . Let us make a quantitative estimation of the magnitude of these parameters, since the critical temperature of the transition of a substance to the superconducting state depends on them significantly (see (3) and (4)).

In the process of "metallization" of semimetals, the pressure causes a change in the structure of the energy spectrum of electrons in these substances. The transition to the "degenerate" state of electrons must be accompanied by a shift in the Fermi level so that the energy spectrum of electrons becomes similar to the spectrum of electrons of ordinary metals. In this case, the total number of charge carriers  $N$  in semimetals is substantially less than in metals. As a result, for "metals" obtained under the action of pressure from semimetals, the calculated value of the Fermi energy, in order of magnitude, is only  $\approx 3 \cdot 10^{-2} \text{ eV}$ .

As for the characteristic states number  $N^*$  directly at the Fermi level, it has approximately the same value as in ordinary metals [17]. Therefore, taking into account relation (6) and the value of the Fermi energy for ordinary metals with superconductivity, for example, Al, about 10 eV, we can estimate the dimensionless coefficient  $\chi$  characterizing a possible increase in the parameter  $n_s^*$  for semimetals under pressure. This coefficient (the ratio of the corresponding values of the Fermi energy) is  $\approx 3 \cdot 10^2$  in order of magnitude (see (6)). Consequently, the estimated value of the pairing constant  $\lambda$  for metals obtained from semimetals under a pressure of  $\approx 10^7 \text{ Pa}$  can reach  $\lambda \approx \chi \cdot \lambda_0 \approx 10^2$  ( $\lambda_0 \approx 0.3$  is the characteristic value of the pairing constant for "low-temperature" superconducting metals and compounds). With this  $\lambda$ , the estimated value of the critical temperature  $T_c$  can reach  $T_c \approx 2\Theta$  (see (3)). Thus, the expected critical temperature of the transition to the superconducting state under a pressure of  $\approx 10^7 \text{ Pa}$  should be characterized by the value of  $T_c \approx 200 \text{ K}$  for Bi, and  $\approx 400 \text{ K}$  for Sb.

Of course, it must be taken into consideration that the "metallization" of a substance is only one of the necessary conditions for the manifestation of superconductivity. As already indicated, another important condition for the existence of a superconducting state of a substance is the formation of a crystal structure with the presence of high-frequency phonons. We'll show that this condition can also be realized to some extent, if not only elements of semimetals are used for the synthesis of a superconducting compound, but also solid solutions based on them. The next section of this paper is devoted to the discussion of this possibility. As before, for concreteness, alloys made of two semimetals Bi and Sb are considered.

#### **4. The formation of high-frequency phonons in solid solutions $\text{Bi}_{1-x}\text{Sb}_x$**

In addition to the features of the metallization process of semimetals described in the previous section, these materials also have other specific properties that can contribute to the manifestation of superconductivity. In particular, they have the ability to form a special structural state of the crystal lattice, characterized by the presence of high frequency phonons. This statement is based on data on the features of the formation of solid solutions based on semimetals.

The Bi and Sb atoms have a very small difference in atomic radii ( $\approx 7.5\%$ ), so they can form a continuous series of solid solutions. This is evidenced by the phase diagram in the shape of a cigar [18]. In the studied  $\text{Bi}_{1-x}\text{Sb}_x$  alloys, at certain  $x$ , a simultaneous change in electrical conductivity, heat capacity, thermal conductivity, etc. was observed [19]. The close correlation between the change in these properties and the change in the parameter  $x$  indicates that there is a strong electron-phonon interaction in these materials. The reason for this effect is a special mechanism the formation of the crystal structure of these solid solutions, accompanied by the so-called percolation effect [20, 21]. This phenomenon is as follows.

During crystallization under normal conditions, the elements Bi and Sb form a crystal lattice of the  $\alpha\text{-As}$  ( $A_7$ ) type (space group  $R\bar{3}2/m$ ). In a lattice of this type, atoms are located in two parallel planes, so that each atom of one plane has three nearest neighbors belonging to another plane, as

well as three neighbors at a greater distance in the adjacent layer. As a result of this spatial arrangement of atoms, the crystal lattice is close in its properties to a conventional face-centered "pseudo-cubic" lattice. This type of crystal lattice remains unchanged during the formation of solid solutions  $\text{Bi}_{1-x}\text{Sb}_x$ . However, as X-ray analysis shows, in these compounds, when the parameter  $x$  changes, processes of additional self-organization of foreign atoms with respect to the atomic lattice of the base matrix take place (percolation effect). At the initial stage of the solution formation process, upon reaching a certain value  $x \approx x_c$  ( $x_c$  is the so-called percolation threshold), structural elements with short-range order (clusters) are formed from impurity atoms. As the concentration of foreign atoms increases, the process of crystallization of the virtual "liquid" phase occurs, that is, the formation of a "superstructure", characterized by long-range order.

It is natural to assume that such specific changes in the structure of the described compounds  $\text{Bi}_{1-x}\text{Sb}_x$  must be accompanied by a change in the phonon spectrum, including the appearance of high frequency phonons. This is evidenced by the results of studies of the thermal properties of the described alloys (heat capacity, thermal conductivity), as well as other physical properties associated with phonons. We emphasize that the full effect of percolation occurs only when the threshold value  $x_c$  reaches  $\approx 0.25$  (when bismuth is the basic element) or  $\approx 0.6$  (when antimony is the basic element).

Thus, since there is a close relationship between the phonon spectrum of a substance and the structure of the energy spectrum of electrons, it is natural to assume that the appearance of an ordered "superstructure" in the crystal lattice should determine the change in the electrical properties of the described compounds, in particular, contribute to the manifestation of the effect of superconductivity.

#### **5. Conclusions**

Based on the analysis and quantitative estimates, the following conclusions can be drawn.

Semimetals Bi and Sb as well as solid solutions based on them  $\text{Bi}_{1-x}\text{Sb}_x$  under pressure  $\approx 10^7$  Pa can be transformed into a metallic state characterized by a sufficiently high degree of "collectivization" of valence electrons. Under the action of pressure, the energy spectrum of the electrons

of these materials becomes similar to the spectrum of "degenerate" electrons in ordinary metals, i.e., particles with energy states described by the quantum Fermi-Dirac statistics. In this case, however, the Fermi energy of these substances has a value of  $\approx 0.03$  eV which is two orders of magnitude less than the average Fermi energy of common metals.

The small value of the Fermi energy in "metallized" semimetals causes an increase in the pairing constant  $\lambda$  in these substances to a value of  $\approx 10^2$ , i.e., the electron-phonon interaction is significantly enhanced. Accordingly, an increase in the constant  $\lambda$  should lead to an increase in the critical temperature  $T_c$  of the transition to the superconducting state up to  $\approx 300$  K.

In solid solutions of semimetals  $\text{Bi}_{1-x}\text{Sb}_x$ , when certain values of the parameter  $x$  (percolation thresholds) are exceeded, a "superlattice" of foreign atoms is formed. Such a specific structural state causes a change in the nature of the phonon spectrum (an additional number of high-frequency phonons appears). This circumstance leads to an increase in the Debye temperature  $\Theta$ , which contributes to an increase in the critical temperature  $T_c$ .

Thus, semimetals and their alloys under a pressure of  $\approx 10^7$  Pa can be the new "high-temperature superconductors" with a transition temperature of  $\approx 300$  K.

### References

1. J.Bardeen, L.N.Cooper, J.R.Schrieffer, *Phys. Rev.*, **108**, 1175 (1957).
2. J.G.Bednorz, K.A.Muller, *Z. Phys., Condens. Matter.*, **B64**, 189 (1986).
3. M.K.Wu et al., *Phys.Rev.Lett.*, **58**, 908 (1987).
4. F.C.Zhang, T.M.Rice, *Phys.Rev., Condens. Matter.*, **B37**, 3759 (1988).
5. R.V.Vovk, A.L.Solovyov, *Low Temper. Phys.*, **44**, 81 (2018). <https://doi.org/10.1063/1.5020905>.
6. A.L.Solovjov, E.V.Petrenko, L.V.Omelchenko et al., *Sci. Rep.*, **9**, 9274 (2019). <https://doi.org/10.1038/s41598-019-45286-w>.
7. A.L.Solovjov, L.V.Omelchenko, E.V.Petrenko et al., *Sci. Rep.*, **9**, 20424 (2019). <https://doi.org/10.1038/s41598-019-55959-1>.
8. Y.Li, J.Hao, H.Liu et al., *J. Chem. Phys.*, **140**, 174 (2014).
9. A.P.Drosdov, M.I.Eremets, I.A.Troyan et al., *Nature*, **525**, 73 (2015).
10. N.W.Ashcroft, *Phys. Rev. Lett.*, **92**, 187002 (2004).
11. F.Peng, Y.Sun, C.J.Pickard et al., *Phys. Rev. Lett.*, **119**, 107007 (2017).
12. H.Liu, I.I.Naumov, R.Hoffman et al., *Proc. Nat. Acad. Sci.*, **114**, 6990 (2017).
13. M.Somayzulu, M.Ahart et al., *Phys. Rev. Lett.*, **122**, 027001 (2019).
14. Yu.I.Boyko, V.V.Bogdanov, R.V.Vovk, *Fiz. Nizkich Temperatur*, **46**, 658 (2020).
15. V.Kresin, H.Gutfreund, W.Little, *Sol.State Common.* **51**, 339 (1984).
16. M.P.Slavinskij, *Fiziko-chimicheskie Svoystva Elementov (1952) [in Russian]*.
17. A.S.Davydov, *Teoriya Tverdogo Tela*, Nauka, Moscow (1976) [in Russian].
18. Ya.A.Ugaj, *Fazovoe Ravnovesie Mezhdru Fosforom, Myshyakom, Sur'moj i Vismutom*, Nauka, Moscow (1989) [in Russian].
19. K.Malik, D.Das et al., *J. Appl. Phys.*, **112**, 083706 (2012).
20. A.N.Doroshenko, *Dissertatsiya*, Universitet KhPI, Kharkov (2019).
21. D.Stauffer, A.Aharony, *Introduction to Percolation Theory*, Washington, Taylor and Francis (1992).