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Photoacoustic effect and superconductivity of metals

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The possibility of using the photoacoustic effect to transform metals into a superconducting state at room temperature is discussed. Laser radiation with a wavelength $\simeq 5 \cdot 10^{-6}$ m and pulse duration $\simeq 10^{-8}$ s when the laser power density is reached $\simeq 10^{12}$ W/m^2 can cause in the volume of metal a shock wave up to $\simeq$10 GPa. The shock wave is accompanied by the generation of phonons characterized by a frequency that is an order of magnitude higher than the analogous parameter in metals, which increases the Debye temperature to a value $\simeq 10^3$ K, and, accordingly, increases the value of the electron pairing constant $\lambda > 1$. In accordance with the microscopic theory of superconductivity in metals (BKS theory), an increase in these parameters should lead to an increase in the critical temperature of the metal transition to the superconducting state. According to estimates, the transition temperature can reach a value close to room temperature.

Keywords: high-temperature superconductivity, photoacoustic effect, electron-phonon interaction.

Фотоакустичний ефект і надпровідність металів. *Ю.І.Бойко, В.В.Богданов, Р.В.Вовк, Б.В.Гриньов*

Обговорюється можливість використання фотоакустичного ефекту для переводу металів до надпровідного стану при кімнатній температурі. Лазерне випромінювання з довжиною хвилі $\simeq 5 \cdot 10^{-6}$ м і тривалістю імпульсу $\simeq 10^{-8}$ с за досягнення щільності потужності лазера $\simeq 10^{12}$ Вт/м^2 може викликати в об'ємі металу ударну хвилю величиною до $\simeq$10 GPa. Ударна хвиля супроводжується генерацією фононів, що характеризуються частотою, яка на порядок величини перевищує аналогічний параметр у металах, збільшує температуру Дебая до величини $\simeq 10^3$ К, і, відповідно, збільшує значення константи спарювання електронів $\lambda > 1$. Відповідно до мікроскопічної теорії надпровідності у металах (теорії BKS), збільшення зазначених параметрів має привести до збільшення критичної температури переходу металу до надпровідного стану. Згідно з оцінками, температура переходу може досягати значення близького до кімнатної температури.

Обсуждается возможность использования фотоакустического эффекта для перевода металлов в сверхпроводящее состояние при комнатной температуре. Лазерное излучение с длиной волны $\simeq 5 \cdot 10^{-6}$ м и длительностью импульса $\simeq 10^{-8}$ с при достижении плотности мощности лазера $\simeq 10^{12}$ Вт/м^2 может вызвать в объеме металла ударную волну величиной до $\simeq$10 GPa. Ударная волна сопровождается генерацией фононов, характеризующихся частотой на порядок величины, превышающей аналогичный параметр в металлах, что увеличивает температуру Дебая до величины $\simeq 10^3$ К, и, соответственно, увеличивает значение константы спаривания электронов $\lambda > 1$. В соответствии с микроскопической теорией сверхпроводимости в металлах (теорией BKS), увеличение указанных параметров должно привести к увеличению критической температуры перехода металла в сверхпроводящее состояние. Согласно оценкам, температура перехода может достигать значения близкого к комнатной температуре.

1. Introduction

Electrical superconductivity (zero electrical resistance) of metals is a unique physical property that is important for fundamental science and is successfully used in modern technical devices [1–3]. The main factor limiting the widespread use of this effect in practice is that superconductivity of metals is realized at very low temperatures (≈1÷20 K). This fact complicates the use of superconductivity of metals in the technique, and its implementation is economically disadvantageous. In this regard, an urgent task of modern materials science is the search for new (not only metallic) superconducting substances, as well as finding additional conditions under which superconductivity of metals would be realized at a higher temperature than is currently observed. In this case, a highly desirable and most effective end result of these exploratory studies would be the discovery of superconductivity at temperatures close to room temperature ($\simeq$300 K).

An important successful step in solving this problem was the discovery in 1986–1987 of the so-called "high-temperature" superconductors [4–6]. They turned out to be complex multicomponent compounds (metal oxides), for example, YBaCuO, HgBaCaCuO and others. The critical temperature of the transition to the superconducting state of these compounds exceeded the boiling point of liquid nitrogen ($\approx$ 77 K) — a relatively cheap refrigerant. However, the discovery made did not fully solve the above problem, since the record value of the critical temperature of the transition T_c into the superconducting state of these compounds only reached $\simeq$ 164 K.

The next very significant achievement in solving the described problem was the discovery of superconductivity in compounds of metals with hydrogen (hydrides) [7, 8]. For example, it was found that the temperature T_c for the LaH_{10} compound reaches the value $\simeq$ 250 K, which is very close to room temperature. However, superconductivity in hydrides is realized only under significant pressure > 150 GPa.

Thus, based on the objective information presented above, we can conclude that the task of searching for new, technically acceptable conditions under which the transition of metals into a superconducting state at room temperature can be realized is still very urgent.

In this paper, we discuss the possibility of achieving this purpose under conditions of artificial generation of additional high-frequency phonons in a metal when the metal is irradiated with a powerful light flux (photoacoustic effect).

2. Physical concept and theoretical estimates

Currently, clearly established that the main mechanism of superconductivity in metals is the electron-phonon interaction. The microscopic theory of this mechanism was developed in 1957 by Nobel laureates (Bardeen, Cooper, Schrieffer) and is known in the scientific world as the BCS theory [9]. According to this theory, as a result of electron-phonon interaction in a metal, under certain conditions, bound pairs of electrons (Cooper pairs) are formed, which can transfer an electric charge without scattering and, accordingly, without energy consumption (electrical superconductivity). In accordance with the BCS theory, the relationship that characterizes the critical temperature of a metal transition into a superconducting state has the form:

$$T_c \simeq \theta \exp[-1/(\lambda - \mu)]. \qquad (1)$$

Here θ is the characteristic temperature (Debye temperature) of the metal, which is specified by the maximum frequency of the phonon spectrum ν^{max}: $\theta = h\nu^{max}/k$ (h is Planck's constant, k is Boltzmann's constant, λ is the electron pairing constant, μ is the so-called Coulomb pseudopotential, which takes into account direct electron-electron repulsion (as a rule, $\mu \simeq 0.1$–0.15). Relation (1) is fulfilled for a relatively weak pairing of electrons, i.e. at values $\lambda < 1$. So, for example, at the value of the Debye temperature $\theta \approx 100$ K (the typical order of this parameter magnitude for metals) and by $\lambda \simeq 0.3$ (assuming that $\mu \simeq 0$), in accordance with (1), we have: $T_c \approx 5$ K. This quantitative estimate is in good agreement with experimental data. It also follows from relation (1) that the critical temperature T_c can be increased if an additional amount of high-frequency phonons is excited in the metal, i.e., in fact, to realize the desired effect, it is necessary to change the phonon spectrum of the metal in such a way that the Debye temperature increases. For metals, the Debye temperature is determined by the maximum frequency $\nu^{max} = v/2a$, where v is the speed of sound, a is the crystal lattice parameter. Since in order of magnitude $v \simeq 10^3$ m/s, and the lattice parameter: $a \simeq 2\cdot10^{-10}$ m, then the value ν^{max} is $\simeq 2\cdot10^{12}$ 1/s. Accordingly, for most classical metals, the values of the Debye temperature are characterized by an interval from $\simeq$100 to 300 K. Thus, it can be assumed that with artificial excitation of a sound wave with a frequency $\nu > \nu^{max}$ in a metal, it is possible to achieve an increase in the Debye temperature of the metal and, accordingly, an to increase in the critical temperature of its transition to the superconducting state.

An increased frequency of vibrations of atoms in metals can be caused by irradiating the metal with a stream of light of a certain power. This is evidenced by the existence of the so-called photoacoustic effect [10]. According to the authors of [10], the flux of photons created by a laser and having a power density $\simeq 10^{12}$ W/m^2 at pulse duration $\simeq 10^{-8}$ s, creates on the metal surface a shock wave of magnitude $P \simeq 10$ GPa. Accordingly, a sound wave arises in the volume of the metal, the frequency of which is given by the relation

$$\nu \simeq 3P/hn_{ph}. \qquad (2)$$

Here n_{ph} is the phonon density, the value of which, in turn, can be estimated using the following relation:

$$n_{ph} \simeq 3kT/h\nu^{max}a^3. \qquad (3)$$

Substituting in relations (2) and (3) the numerical values of the constants, as well as the values of P, a, ν^{max} and $T \simeq 300$ K (room temperature) we obtain $\nu \simeq 5\cdot10^{13}$ 1/s. Thus, irradiating a metal with laser pulses of average power, it is possible to ensure the presence of phonons in its phonon spectrum, the frequency of which is more than an order of magnitude higher than the characteristic value μ^{max}. In this case, the wavelength of the laser beam L, capable of providing the generation of an acoustic wave of the specified frequency ν, is characterized by the value $\simeq 5\cdot10^{-6}$ m, which corresponds to the lower limit of the infrared region of light radiation. Lasers with the above radiation parameters are now widely used and, therefore, the generation of a high-frequency sound wave in metals using pulsed laser irradiation is technically quite realizable [11]. It should be borne in mind the following important circumstance. An increase in the Debye temperature of a superconductor can also cause an increase in the electron pairing constant λ. So, for example, the pairing constant λ for hydrides, due to the smallness of the crystal lattice parameter and the low mass of hydrogen atoms, according to different estimates reaches the values $\approx 2\div5$. With such a "strong" pairing, relation (1) is not applicable and instead of it another relation is fulfilled:

$$T_c \simeq 0.2\theta\sqrt{\lambda} \qquad (4)$$

(it is assumed that the Coulomb pseudo-potential $\mu \simeq 0$) [12].

Thus, based on the estimates made, it can be concluded that a metal with artificially created high-frequency phonons should be characterized by an increased value of the Debye temperature $\simeq 10^3$ K. If, in this case, the pairing constant increases, for example, to a value of ≈ 4, then, in accordance with (4), the critical temperature of the transition to the superconducting state can reach the value $T_c \simeq 400$ K. Of course, this value of T_c is an estimate, but it indicates that metals under conditions of laser irradiation of a certain power can become superconductors at temperatures close to room temperature.

3. Conclusions

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

Using laser light with a wavelength $\simeq 5\cdot10^{-6}$ m and pulse duration $\simeq 10^{-8}$ s when the laser power density is reached $\simeq 10^{12}$NW/m^2 it is possible to cause a shock wave in the volume of the metal up to $\simeq$ 10 GPa.

As a result of the photoacoustic effect, a shock wave caused by laser irradiation accompanied by the generation of phonons characterized by a frequency $\simeq 10^{13}$ 1/s which is an order of magnitude higher than the maximum value of this parameter in metals.

Artificial generation of high-frequency phonons can cause an increase in the Debye temperature to the value $\simeq 10^3$ K, as well as an increase in the value of the electron pairing constant $\lambda > 1$. Consequently, according to the estimates made, the critical temperature of the transition to the superconducting state of a metal irradiated by laser pulses can reach a value close to room temperature.

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