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Tunneling Conductivity in the Normal Phase of Superconducting Indium in Porous Glass

O.N. Ivanov, I.V. Sudzhanskaya

Belgorod State University, 85, Pobedy Str., 308015 Belgorod, Russia

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Electrical resistance of indium in 7 nm-pore glass has been studied in the temperature 2.3-300 K interval. It was found that material under study undergoes the transition into the superconducting state at $T_C = 3.9$ K. A sharp asymmetric $R(T)$ maximum was found at temperature of 6.4 K. The $R(T)$ dependence has been for the first time analyzed for the normal phase. It was found that the temperature dependence of the resistance in the temperature 15-80 K interval can be described by tunnelling mechanism of the charge carriers in the frames of the Sheng's model. Material under study can be considered as electrically inhomogeneous material in which metallic domains in pores are contacting each other via dielectric bridges of glass matrix. A charge transfer between the metallic domains can be realized by the electron tunneling through the potential barriers corresponding to the dielectric bridges.

Keywords: Porous glass, Indium, Superconducting transition, Tunneling conductivity.

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1. INTRODUCTION

Nanoporous materials filled with different substances (polymers, ferroelectrics, superconductors, etc.) can be considered as nanostructured composites [1]. Such composites demonstrate specific physical properties and have wide prospects of their practical applications. Superconducting metals embedded into nanosized pores of the glass matrix form one of nanostructured composites types. To date indium [2-4], gallium [2] and tin [5] were often used as a filling superconducting metal. At present the superconducting properties of metals embedded into the nanoporous glass matrix have been studied in detail [2-5]. It was found that main superconducting characteristics of these materials are significantly modified in comparison with the bulk pure metals. For instance, the nanostructured composites consisting of glass matrix filled with some superconducting metal are characterized by the enhanced value of a superconducting transition temperature, T_C (T_C value is 20 % or more higher than T_C of the bulk pure metal), the change in behaviour under external magnetic field from the type-I superconductor to the type-II superconductor, the high value of an upper critical field (critical field is 100 times greater in comparison with the bulk pure type-I metal), etc. However, researches of metals in porous glass have been usually limited to low-temperature field in the vicinity of T_C. It is obviously that superconductivity is originating from a normal phase. So, specific properties of the normal phase should be also investigated to understand peculiarities in physical behaviour of metals in porous glass in the wide temperature interval including the superconducting transition.

The aim of this paper is to find and analyze the peculiarities in behaviour of electrical resistance of indium in the porous glass in the temperature field including both the superconducting transition and the wide temperature (from T_C up to room temperature) interval of the normal phase.

2. EXPERIMENTAL PROCEDURE

The porous glass was prepared by leaching a sodium borosilicate glass to remove the boron-rich phase and leave the porous matrix. The porous glass after leaching was cleaned by H_2O_2. To remove H_2O_2 from the porous glass, it was then heated to temperature of 400 K in the air atmosphere. The average size of the pores measured by the mercury-intrusion-porosimetry method was estimated to be equal to ~7 nm. Liquid indium was embedded into the porous matrix under high pressure of 9 Kbar at temperature of 440 K.

Electrical resistance, R, was measured by a four-probe method at direct current of 0.1 mA. The resistance was measured by averaging the voltage values obtained for the forward and the reverse current directions. External magnetic field perpendicular to the current direction can be applied to the sample during the $R(T)$ measurements.

3. RESULTS AND DISCUSSION

The temperature dependence of R for the temperature interval from the lowest temperature 2.3 K up to room temperature is presented in Figure 1. To show details of the $R(T)$ dependence more clearly, the R-axis onset is positioned at $R = 3.15\ \Omega$ in Figure 1. This dependence can be divided into two parts. At first the resistance rapidly increases at cooling from room temperature, but below ~ 6.4 K the $R(T)$ dependence drops drastically. So, a sharp asymmetric maximum in the $R(T)$ dependence is observed at temperature $T_m \approx 6.4$ K. A ratio of $R(300\text{ K})/R(6.4\text{ K})$ characterizing the resistance increasing at cooling is equal to ~ 1.22. It should be noted that a small curvature in the $R(T)$ dependence is also observed just below room temperature.

Let us discuss the $R(T)$ dependence of indium in the porous glass in detail. The rapid R falling to zero value at cooling is characteristic for the superconducting transition.

The $R(T)$ dependence taken for the temperature 2-12 K interval is presented in Figure 2. Now the R-axis onset is positioned at $R = 0\ \Omega$. One can see that the resistance really vanishes at $T_C = 3.9$ K. So, the sample under study is superconductor. It is known [6] that the superconducting transition temperature of the bulk pure indium is equal to 3.41 K. Thus, the T_C value for indium in the porous glass is enhanced over the value of the bulk pure indium by 14 %. The T_C value for our sample under study is in satisfactory agreement with results of Refs. [2-4]. The enhanced T_C is believed [2] to arise from large surface-to-volume ratio, which enhances the electron-phonon coupling constant, and thus T_C.

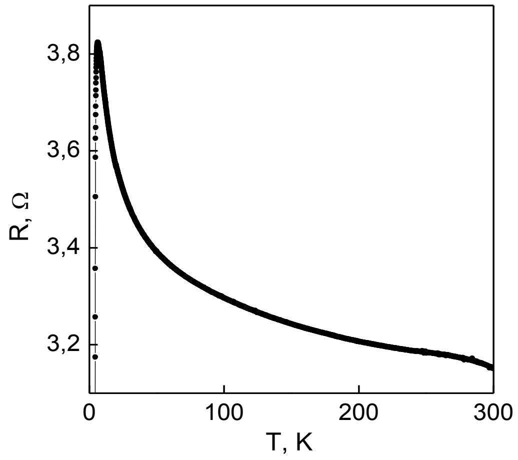

Fig. 1 – The $R(T)$ dependence of indium in porous glass

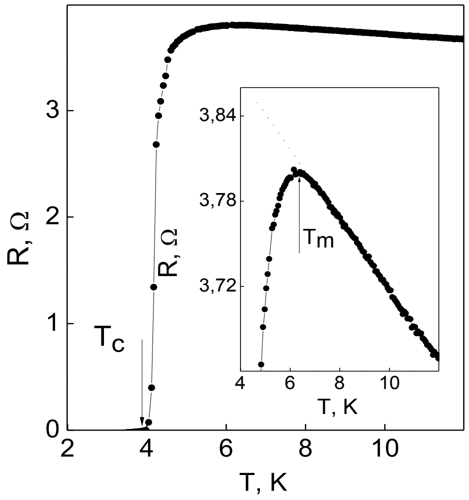

Fig. 2 – The $R(T)$ dependence in the vicinity of the superconducting transition temperature T_C. The inset is the $R(T)$ dependence around temperature Tm

As was mentioned above, the sharp $R(T)$ maximum is observed at the superconducting transition. The inset in Figure 2 shows this maximum in details for the temperature 4-12 K interval. Above T_m the experimental $R(T)$ curve demonstrates the linear T-dependence, which satisfactory obeys the expression $R(T) = 3.96\ (\Omega) - 2.5\cdot 10^{-2}\ (\Omega\cdot K^{-1})\cdot T(K)$.

The width of the superconducting transition was estimated as $\Delta T = T_m - T_C = 2.5$ K.

It should be noted that double-step resistive superconducting transition were observed for indium in the porous glass [2, 3]. However, our sample under study demonstrated one-step resistivity superconducting transition.

It is known that the superconducting state is destroyed under an external magnetic field. Figure 3 shows the magnetic field effect on the superconducting transition of indium in the porous glass. One can see that the magnetic field increasing leads to a shift of the superconducting transition to the lower temperatures. Superconductivity at 2.3 K is still observed under high magnetic field of 3.5 T. The critical magnetic field value at 2.5 K for the bulk pure type-I indium is equal to 0.0125 T [6]. So, the critical magnetic field for the nanostructured composite under study is much higher than the critical field for the bulk pure indium. As was mentioned above, indium in the porous glass under the external magnetic field behaves as the type-II superconductor. In this case, a complete suppression of the superconductivity will take place at the upper critical magnetic field.

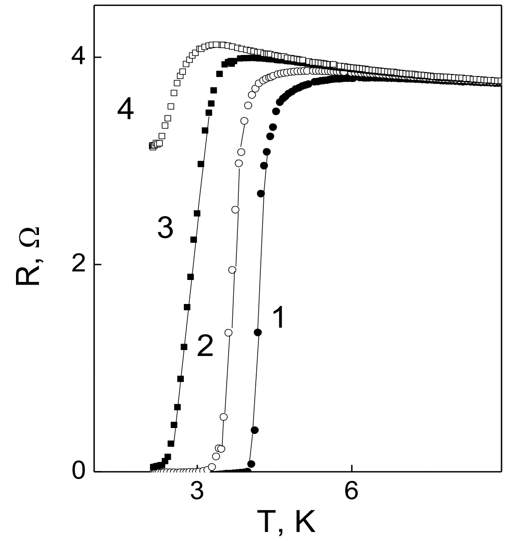

Fig. 3 – The $R(T)$ dependences measured at various values of external magnetic field: 0 (curve 1), 2 (2), 3.5 (3) and 4.5 T (4)

To take into account the enhanced critical field of the nanostructured composites, a granular structure composite was assumed, where the grain size was limited by the pore size [2]. Then, the resulting decrease in the electron mean free path reduces the coherence length, ξ, from the bulk value. The upper critical magnetic field is related to ξ via [2]

$$B_{c2} = \frac{\Phi_0}{2\pi}\left[\xi(T)\right]^{-2}, \quad (1)$$

where Φ_0 is the magnetic flux quantum.

According to expression (1), the upper critical magnetic field will really increase as ξ decreases.

Detailed study of the magnetic field effect on the superconducting properties of indium in the porous glass is in progress. Here Figure 3 is just given as an additional experimental fact confirming the superconductivity appearance in the sample under study.

Now let us analyze the $R(T)$ dependence of indium in the porous glass in the normal phase above Tm. For these temperatures the $R(T)$ dependence is rapidly decreasing as temperature increases. Such kind of the $R(T)$ behaviour is characteristic of semiconductors and due to the thermal generation of the carries at heating. But the bulk pure indium is metal. It means that the resistance of indium increases at temperature increases [6]. To explain the $R(T)$ dependence of indium in the porous glass in the normal phase, the structural peculiarities of this nanostructured composite should be considered on a micro- and nanoscale.

According to Ref. [3], in these nanostructured composites, the nanosized pores together with narrow necks, which connect with pores, form the random interconnected network in the porous glass. Moreover, the pores filled with metal will have metallic type on conductivity, while the narrow glass necks will be dielectric. So, such a kind of the nanostructured composite should be considered as an electrically inhomogeneous material in which metal domains are contacting each other via dielectric bridges. A charge transfer between the metallic domains can be realized by an electron tunneling through potential barriers corresponding to the dielectric bridges. Tunneling mechanism of conductivity of any solid under study can be confirmed by comparison of the experimental temperature dependence of the conduction (or the resistance) with the theoretical predictions of the tunneling conductivity model.

One of the tunneling conductivity models is the Sheng's model [7]. This model was firstly proposed to explain the electric properties of granular metals consisting of small crystalline metal grains embedded in a dielectric matrix. It is known [8] that the temperature dependence of the specific electrical resistivity, ρ, of the granular metals can be expressed in the form $\rho \sim \exp(-b/T^{-1/2})$.

According to the Sheng's model, the electrical conductivity in the granular metals is determined by hopping conductivity and results from the thermally activated transport of electrons from charged metal grains to neutral grains via tunneling. To generate a charge carrier, an electron has to be removed from the neutral grain and placed on a neighboring neutral grain. Such a process required an energy $E_c = (e^2/d)F(s/d)$, where e is the electronic charge, d is the grain size, s is the separation between the grains, and F is a function whose form depends on shape and arrangements of the grains.

The temperature dependence of the specific electrical resistivity of the granular metals in the Sheng's model can be expressed as

$$\rho = \rho_0 \exp\left\{ 2\left(\frac{C}{k_B}\right)^{1/2} T^{1/2} \right\}, \qquad (2)$$

where C is the activation energy of tunneling, k_B is the Boltzmann constant and ρ_0 is the pre-exponential constant.

In accordance with expression (2), the ln$R$ versus $T^{-1/2}$ dependence was plotted (Figure 4).

One can see that this dependence is linear one for the temperature interval from $T_1 = 15$ K up to $T_2 = 80$ K. So, the $R(T)$ dependence of indium in the porous glass can be determined by the tunneling conductivity for this temperature interval.

The arising $R(T)$ dependence due to the tunneling conductivity combined with the falling $R(T)$ dependence due to the superconducting transition leads to appearance of the resistance maximum in Figure 1.

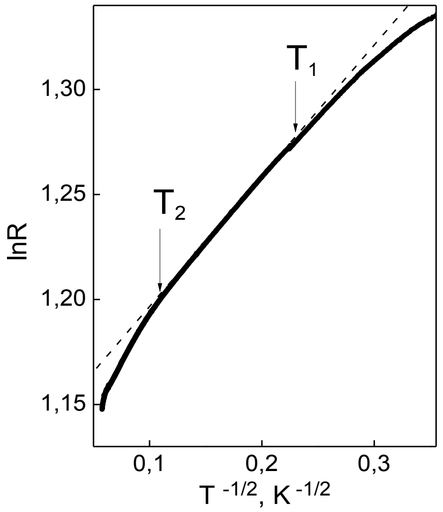

Fig. 4 – The ln$R$ vs. $T^{-1/2}$ dependence

It is obviously that the temperature interval from T_m up to T_1 is a transient temperature field between the tunneling conductivity and the superconductivity.

Further researches should be done to establish a relationship between the electrical properties of the normal phase and the superconductivity of indium in the porous glass.

4. CONCLUSIONS

The temperature dependence of the resistance of indium in the porous glass has been measured within wide temperature interval from 2.3 up to 300 K. The superconducting transition was observed at $T_C = 3.9$ K. The sharp asymmetric $R(T)$ maximum was found at $T_m = 3.9$ K. The $R(T)$ dependence has been for the first time analyzed for the normal phase. It was found that the temperature dependence of the resistance in the temperature 15-80 K interval can be described by the tunnelling mechanism of the charge carriers.

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Туннельная проводимость сверхпроводящего индия в пористом стекле

О.Н. Иванов, И.В. Суджанская

Белгородский государственный университет, ул. Победы, 85, 308015 Белгород, Россия

Электрическое сопротивление индия индия в пористом стекле с размером пор 7 нм было изучено в интервале температур 2,3-300 K. Обнаружено, что исследуемый материал претерпевает переход в сверхпроводящее состояние при температуре $T_C = 3{,}9$ K. Резкий ассиметричный пик на кривой $R(T)$ обнаружен при температуре 6,4 K. Впервые $R(T)$ зависимость проанализирована для нормальной фазы. Установлено, что в интервале температур 15-80 K температурная зависимость сопротивления описывается механизмом туннелирования носителей заряда в рамках модели Шенга. Исследуемый материал можно рассматривать как электрически неоднородный материал, в котором металлические области в порах контактируют между собой посредством диэлектрических мостиков матрицы из стекла. Перенос заряда между металлическими областями происходит посредством туннелирования электронов через потенциальные барьеры, соответствующие диэлектрическим мостикам.

Ключевые слова: Пористое стекло, Индий, Сверхпроводящий переход, Туннельная проводимость.

Тунельна провідність надпровідного індію в пористому склі

О.Н. Іванов, І.В. Суджанская

Белгородський державний університет, вул. Перемоги, 85, 308015 Белгород, Росія

Електричний опір індію індію в пористому склі з розміром пор 7 нм було вивчено в інтервалі температур 2,3-300 K. Виявлено, що досліджуваний матеріал зазнає перехід в надпровідний стан при температурі $T_C = 3{,}9$ K. Різкий асиметричний пік на кривій $R(T)$ виявлений при температурі 6,4 K. Вперше $R(T)$ залежність проаналізована для нормальної фази. Встановлено, що в інтервалі температур 15-80 K температурна залежність опору описується механізмом тунелювання носіїв заряду в рамках моделі Шенга. Досліджуваний матеріал можна розглядати як електрично неоднорідний матеріал, в якому металеві області в порах контактують між собою за допомогою діелектричних містком матриці зі скла. Перенесення заряду між металевими областями відбувається за допомогою тунелювання електронів через потенційні бар'єри, відповідні діелектричним містках.

Ключові слова: Пористе скло, Індій, Надпровідний перехід, Тунельна провідність.

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