Вісник ХНУ, № 1158, серія «Фізика», вип. 22, 2015. с. 63-67

PACS:

74.78.Fk	Multilayers, superlattices, heterostructures
74.25.F	Transport properties
74.40.Kb	Quantum critical phenomena

УДК 538.945

Influence of transport current on the magnetic field induced superconductor-insulator transition in PbTe/PbS heterostructures

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Transport properties of semiconductor heterostructures PbTe/PbS with a superconducting interface are studied. The influence of the electric current on the resistive state of the heterostructures is investigated. The possibility of the realization of the electric current induced superconductor-insulator transition is shown. The temperature dependence of critical magnetic fields of the transition is obtained.

Keywords: superconductivity, quantum superconductor-insulator transition, semiconductor heterostructures.

Проведено вимірювання транспортних властивостей напівпровідникових гетероструктур PbTe/PbS з надпровідним інтерфейсом. Досліджено вплив транспортного струму на резистивний стан гетероструктур. Продемонстровано можливість реалізації в таких структурах індукованого транспортним струмом переходу надпровідник-ізолятор. Одержано залежність критичного магнітного поля переходу від температури.

Ключові слова: надпровідність, квантовий фазовий перехід надпровідник-ізолятор, напівпровідникові гетероструктури.

Проведены измерения транспортных свойств полупроводниковых гетероструктур PbTe/PbS со сверхпроводящим интерфейсом. Исследовано влияние транспортного тока на резистивное состояние гетероструктур. Продемонстрирована возможность реализации в таких структурах индуцированного транспортным током перехода сверхпроводник-изолятор. Получена зависимость критического магнитного поля перехода от температуры.

Ключевые слова: сверхпроводимость, квантовый фазовый переход полупроводник-изолятор, полупроводниковые гетероструктуры.

Introduction

In this paper we present the results of an experimental study of the influence of electric current and strong magnetic fields on the superconducting state of nanostructures that formed on the interface between semiconducting layers of the epitaxial PbTe/PbS heterostructures [1, 2, 3, 4, 5, 6]. Here, we examine the possibility of the transport current induced quantum superconductor-insulator phase transition (SIT) [4].

Superconductor-insulator phase transitions have been intensively studied for the last time. They are found experimentally in a number of low-dimension systems such as ultrathin amorphous films, granular films, and arrays of Josephson junctions. This phenomenon occurs when the internal parameters of the system (such as disorder or film thickness) change or under the influence of external impact such as magnetic fields *H*, electric fields or transport currents *I*. Superconductor insulator transitions have also been observed experimentally in HTSC compounds and even in one-dimensional long nanowires. Features of SIT depend on the material properties and the experimental conditions [7, 5]. The nature of the superconductor-insulator transition is still an open question.

Interpretation of the superconductor-insulator transition observed experimentally in uniform thin disordered films is sufficiently complicated. As an example, for films with relatively low resistance *R* per square the characteristic features of SIT can be explained by quantum mechanical corrections to the conductivity [6]. In this case, on the insulating side there will be a slight increase of no more than 10% in the resistance. In the case of a large increase in the resistance on the insulating side induced by a magnetic field, the superconductor-insulator transition in uniform thin disordered films is most often explained by Fisher's scaling theory [7] (a theory of duality between Cooper pairs and vortices). It is assumed that at $T\to 0$

delocalized Cooper pairs and localized vortices exist below the transition at $H<H_c$ (superconductor), and localized pairs with delocalized vortices above the transition $H>H_c$ (insulator). The magnetic field and temperature dependence of the resistance per square follow the scaling law for phase transitions $R(\delta T) = R_c F(\delta x / T^{1/\nu z})$, where F is a constant introduced to maintain the dimensionality of the equation; δ is a variable parameter that drives the phase transition, in this case, a magnetic field with $\delta=|H-H_c|$; and, νz is the critical exponent. The model predicts that the critical resistance per square R_c should equal the universal quantum resistance $R_Q = h/4e^2 = 6.5$ kOhm. The scaling law proposed for the resistance by Fisher [10] is in good agreement with a variety of experimental data [see reviews 7, 8]. Nevertheless, many experiments have yielded a large scatter in the values for the critical resistance and the critical exponent νz. Thus, one of the main predictions of Fisher's theory (a universal quantum resistance) is not observed experimentally in all systems during superconductor-insulator transitions.

In granular systems with small granules [8, 9] and artificially prepared regular arrays of Josephson junctions, [10, 11, 12, 13] the SIT can be explained by a competition between the inter-granule Josephson binding energy J and the charge Coulomb energy E_C of an individual granule. When $E_c>>J$ Coulomb blockade predominates. As a result, Cooper pairs become localized and the system transforms into an insulating state. If, on the other hand, the granules are larger, then Coulomb blockade is not effective and SIT takes place due to disruption of the Josephson links by an external impact (e.g., magnetic field). Single particle transport is also blocked because of the need to overcome a potential barrier comparable to the superconductor gap energy [7]. The Josephson coupling between granules is affected by both magnetic field and electric current. Thus it may be possible to observe the transport current induced superconductor-insulator transition.

Here, the two-layer semiconductor PbTe/PbS heterostructures are studied for the SIT. Interest in research on this heterostructures arises from the possibility of creating superconducting nanostructures with different topologies in a controlled fashion at their interface. We have found [3–6] that superconductivity of the interface of $A^{IV}B^{VI}$ heterostructures is related to an inversion of bands in the narrow-band semiconductors (PbTe, PbS, PbSe) owing to inhomogeneous elastic stresses along a network of misfit dislocations produced at the interface during pseudomorphic epitaxial growth. The period of the superconducting nanonetwork is equal to the period of the network of misfit dislocations and ranges from 3.3–40 nm, depending on the combination of semiconductors. For PbTe/PbS heterostructures it equals 5.2 nm. Thus, by varying the heterostructure parameters, such as the thickness of the semiconductor layers and the number of them, we can create arrays of individual quantum dots with weak Josephson links, as well as continuous superconducting nanonetworks and quasi-three dimensional multilayer structures (superlattices). These superconducting nanostructures have properties inherent in 0 -, 1 -, 2 -, and 3-dimensional systems. Thus, semiconducting PbTe/PbS heterostructures can serve as model objects for the study of effects of the localized superconductivity such as the superconductor-insulator transition. In fact, in our previous works the SIT was found in the heterostructures [14, 15].

It was established that the discontinuity of the superconducting interface is a necessary condition for the magnetic field induced superconductor-insulator transition observation and has a significant influence on its features: a fan-like set of resistance curves *R(T),* intersection of the *R(H)* curves and negative magnetoresistance. A scaling analysis based on Fisher's theoretical model was carried out for these samples. No evidence of a SIT was observed in heterostructures with a perfect interface. It appears that the SIT is related to percolation phenomena inherent in granular superconductors. Up to now the effect of transport current on the magnetic field induced SIT in these structures has not been studied. In the present work we investigate the influence of transport current on the magnetic field induced superconductor-insulator transition in heterostructures PbTe/PbS.

Samples preparation and measurement methods

Two-layer heterostructures were fabricated by sequential condensation of the vapors of the corresponding semiconductors on a freshly cleaved (001) surface of single crystal KCl at 520–570K in an oil-free vacuum of 10^{-6} Torr. The thickness d of each layer was 80nm. Deposition rate was monitored *in situ* using a quartz resonator. The first layer on the substrate always was PbS and the second one was PbTe. These semiconductors have a NaCl-type crystal structure with a small misfit (8%) between the parameters of the unit cells. During epitaxial growth the pseudomorphic stress relaxes through formation of a network of edge misfit dislocations at the interface. When a critical thickness d_c of the upper PbTe layer is reached (about 1-2nm) the first islands of misfit dislocation network arise at the interface [6, 16]). Further thickness increase leads to the merging of the islands and at thickness 100 nm a continuous square network of edge misfit dislocations covers the entire interface [6].

Transport measurements were made in a helium cryostat equipped with a 14T superconducting Oxford Instrument magnet. The accuracy of the temperature stabilization was 10^{-3} K. The resistance R was measured by the four-probe method. The direction of the dc transport current I is parallel to the plane of the sample and $\mathbf{I} \perp \mathbf{B}$. The upper critical magnetic fields B_{c2} were determined from the resistive transitions at the point $R = R_n / 2$, where

R_n is the resistance before the superconducting transition.

Experimental data and interpretation

Earlier it was found that two-layer PbTe/PbS heterostructures can be divided nominally into 3 categories [6], although there is no sharp boundary between these categories.

The first category includes samples with semiconducting layer thicknesses d>80 nm. They have a metallic conductivity in the normal state. The ratio of the resistance at room temperature to the resistance before the onset of the superconducting transition ($r=R_{300}/R_n$) varies from 2 to 8. The corresponding critical temperatures T_c lie in the interval 4.2–6.5K. For samples from this category SIT has not been found.

The second category includes samples with thicknesses of 50–80 nm. This category can be referred to as intermediate. A sample in the normal state can exhibit both metallic conductivity and semiconductor behavior. But in any case at low temperatures it enters a superconducting state. The critical temperature ranges from 2.3–3.3K and r ranges from 0.9 to 1.7. Samples from this category always reveal all SIT features [17,18].

The third category includes samples with d<50 nm. The *R(T)* curves in the normal state for these samples are always characterized by a negative resistance coefficient dR/dT above T_c. The resistance per square R_{sq} exceeds 1.5 kOhm and r<1. For these systems T_c is often below 1K and they undergo an unending transition into the superconducting state down to the lowest temperatures at which the experiments were carried out (0.3 K), or they do not go into the superconducting state at all. The samples from this category can reveal initial features of SIT [18].

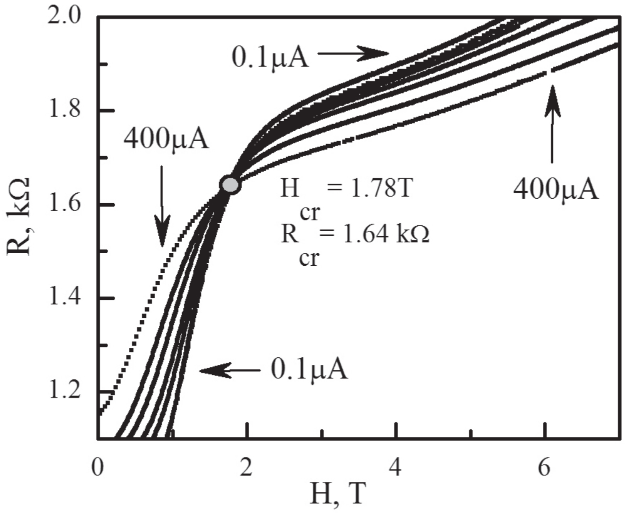

Fig.1. R(H) for different transport currents in a magnetic field parallel to the interface; d=80 nm. T=1.8K.

We will focus our attention on the samples from the second category for which two types of evolution of the *R(T)* curves in magnetic fields were observed. The first type, illustrated in Fig.1 in Ref.17, is characterized by the presence of a horizontal separatrix that clearly separates the $R(T)$ curves which move downward with the temperature decrease (superconductor) from the curves which move upward (insulator). This "fanlike" set of curves is regarded as an "ideal" case of SIT [7] and was observed in the heterostructures with the semiconductor layer thicknesses d=70-80 nm. For samples with d=40-70 nm the second type of the $R(T)$ curves set with tilted or non-monotonic sepratrix is observed [17, 18] which is out of the framework of this article.

For samples with the horizontal separatrix we always see another distinctive sign of the SIT – a single cross point of magnetic field dependences of the resistance $R(H)$ at different temperatures (Fig. 2 in Ref17).

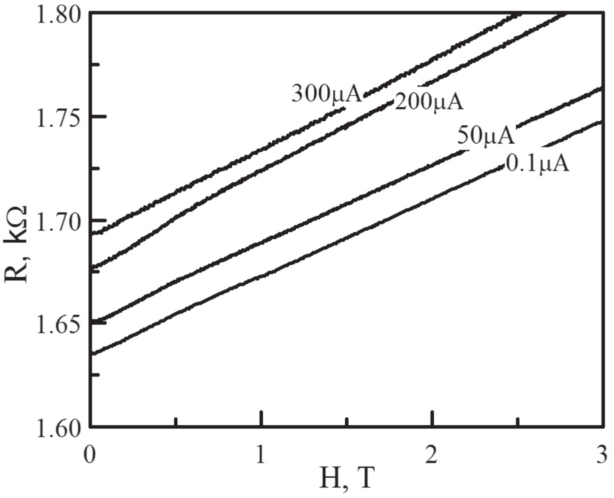

Fig.2. R(H) for different transport currents in a magnetic field parallel to the interface; d=80 nm. T=6.5K.

In this work the resistance dependences on magnetic field at different transport currents and fixed temperature are presented for the PbTe/PbS heterostructure with d=80 nm. It can be seen (Fig.1) that all $R(H)$ curves corresponding to different transport currents intersect precisely at the single point like at different temperatures on the Fig2 in Ref.17. The critical parameters H_{cr} =1.78 T, R_{cr} =1.64 Ohm for the temperature T=1.8K obtained for cross point. At the temperatures higher than critical temperature ($T>T_c$), magnetic field dependences at different transport current do not intersect, and SIT is not observed (Fig.2).

Superconducting areas at the interface may be considered like superconducting granules. Resistance of the whole system is determined by the resistance of granules and intergranular spacers. At sufficiently low temperatures and the absence of external influences the whole system is in a coherent superconducting state. Granules are superconducting, and there are weak Josephson links between them. Magnetic field $H>H_{crSIT}$ breaks weak links. The dissipative state arises. Resistance reaches the maximum because of Cooper pair tunneling through normal regions is blocked by the potential barrier which height is commensurate with the energy of the superconducting gap. Conductivity of the system is now determined only by low probability of single-particle tunneling due to the small number of quasiparticles at the Fermi level. The transport current increase leads to the destruction of superconductivity directly in the superconducting granules (decoupling of Cooper pairs). Number of quasiparticles at the Fermi level rises, the single-particle charge carriers begin to contribute to the conductivity of the system [17] and the resistance decreases (Fig.3).

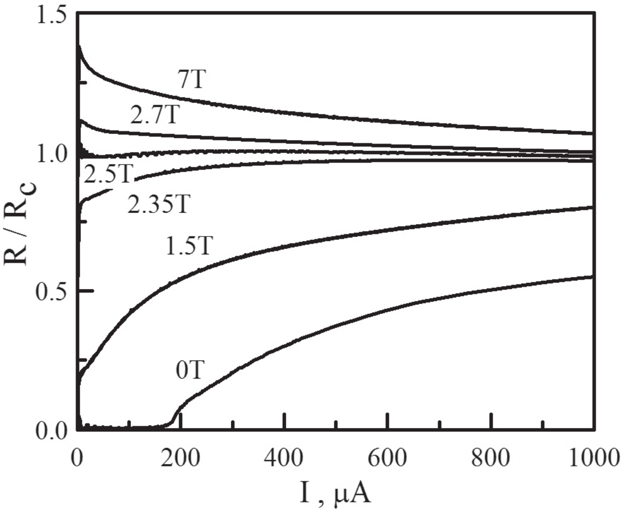

Fig.3. R(I) dependences at different values of parallel magnetic field. *T*=1.5K.

On another side, the transport current increase causes a corresponding increase of voltage at the boundaries of superconducting islands, thus reducing the height of the potential barriers between them. Therefore, the tunneling probability rises and tends to reduce the resistance.

Similar experimental results were obtained in [18] in the thick amorphous bismuth films. The authors of this work suggest a different interpretation of the experimental results within the framework of the hypothesis of overheating of the electron gas. For a final clarification of the mechanism of this phenomenon, we need more experimental data for large values of the transport current in strong magnetic fields.

The temperature dependence of the critical magnetic field of transport current induced SIT is obtained. As seen in Fig.4, the critical field at which we see horizontal separatrix (H_{crSIT}) and cross point on $R(H)$ curves increases with temperature decrease. The dependence $H_{crSIT}(T)$ separates the superconducting state and the state of the localized superconductivity.

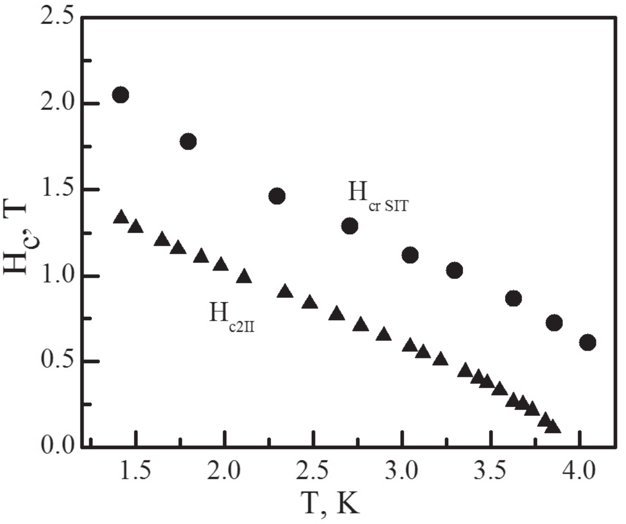

Fig.4. Temperature dependence of the critical magnetic field of SIT and the temperature dependence of upper critical fields.

Thus, for the first time the possibility of transport current assisted the superconductor-insulator transition is shown in superconducting nanostructures based on heterostructures PbTe/PbS. This phase diagram with $H_{c2}(T)$ and $H_{crSIT}(T)$ curves separate the superconducting state and the state of the localized superconductivity.

Acknowledgments

Author is very grateful to A.Yu.Sipatov for technical assistance with the sample preparation and characterization, S.V.Bengus for useful discussion of the experimental results.

Conclusions

1. It is shown that all of the typical features of the SIT (the fan-like set of $R(I)$ dependences at different magnetic fields, the crossing of $R(H)$ curves in a single point at different transport currents) are observed in PbTe/PbS geterostructures with the island-like superconducting interface. The mechanism of the SIT realization is similar to that one which realizes in granular systems with the percolation conductivity. The possibility of realization of a transport current induced superconductor-insulator transition is shown.

2. The dependence of the critical magnetic field of the SIT is obtained.

3. It is shown that $A^{IV}B^{VI}$-type heterostructures can serve as model objects for the study of effects of localized superconductivity, because we can vary the topology of the superconducting interface at the preparation stage.

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