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REGULAR ARTICLE

Near-surface Superconductivity in Topological GaSb and Bi_2Se_3 Whiskers

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Near-surface superconductivity in topologically interesting semiconductor whiskers such as GaSb and Bi_2Se_3 remains an important topic for understanding unconventional pairing mechanisms and the interplay of quantum effects at the nanoscale. Bi_2Se_3 occupies a special place among topological materials due to its strong spin-orbit interaction and robust surface states, which create conditions for realizing topological superconductivity capable of supporting Majorana fermions and novel quantum phases. Inducing superconductivity through controlled doping or self-organized heterointerfaces provides a practical pathway without the need for extreme pressures or complex epitaxial layering, although operation still requires cryogenic temperatures typical for low-T_c superconductors. GaSb whiskers doped with tellurium and Bi_2Se_3 whiskers doped with palladium were synthesized by chemical vapor deposition and examined at cryogenic temperatures down to 1.5 K under magnetic fields up to 14 T. Resistance measurements revealed a sharp drop below 4.2 K in GaSb and below 5.3 K in Bi_2Se_3, indicating partial superconducting transitions likely confined to the near-surface regions. The upper critical magnetic field $B_c(T)$ derived from magnetorsistance data fits the Ginzburg–Landau model, yielding coherence lengths of about 1.7 nm for GaSb and 15 nm for Bi_2Se_3, values comparable to or smaller than those found in high-T_c superconductors, pointing to nontrivial pairing behavior or enhanced spin-orbit-driven mechanisms. Shubnikov-de Haas oscillations observed in GaSb whiskers confirm high crystalline quality and exclude amorphization as the origin of the effect. A transition from weak antilocalization to localization and clear signatures of the Kondo interaction indicate a competition between superconducting pairing and quantum scattering processes. In doped GaSb whiskers near the MIT, partial localization of carriers and their interaction with free electrons leads to suppression of Cooper pairing at elevated temperatures. This coexistence of partial superconductivity, weak localization, and Kondo behavior demonstrates the complex balance of competing electronic correlations in these low-dimensional systems. Such findings expand the understanding of surface-limited superconductivity in topological and A3B5 semiconductor whiskers and provide a foundation for engineering heterostructures capable of hosting exotic superconducting phases useful for quantum devices.

Keywords: Superconductivity, Topological insulators, Whiskers, Weak antilocalization, Kondo effect.

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1. INTRODUCTION

Among the large number of topological materials, the compound Bi_2Se_3 occupies a special place due to its strong spin-orbit interaction and the presence of topologically protected surface states, which allows the implementation of topological superconductivity for the creation of Majorana fermions and topological quantum calculations.

A promising way to induce superconductivity is the creation of heterostructures with metals. In work [1], it was found that when Pd is deposited on the surface of Bi_2Se_3, the spontaneous formation of the intermetallic phase PdBiSe occurs at the interface. This thin layer demonstrates superconductivity with a T_c of about 1.2 – 1.5 K, which is confirmed by TEM analysis [2]. This mechanism makes it possible to implement supeconducting components without the use of doping or extreme conditions.

The theoretical basis for new forms of superconductivity in Bi_2Se_3 is demonstrated in work [3], which models the intercalation of Ag atoms into the interlayer spaces of the crystal. Calculations have shown that silver atoms can significantly change the electronic structure of the material: the Fermi level is shifted upwards and additional charge carriers appear. This leads to an increase in the density of electronic states near the Fermi level $N(E_f)$, which is an important prerequisite for the realization of superconductivity. In addition, it was found that Ag intercalation changes the topological nature of surface states and can contribute to the formation of a favorable electron-phonon environment for the emergence of Cooper pairs. In particular, the calculated values of the electron-phonon constant λ and the pairing parameter indicate the possibility of realizing unconventional superconductivity even at relatively low impurity concentrations. Thus, the Ag-intercalation model complements experimental data on doped structures based on Bi_2Se_3, expanding the understanding of possible scenarios for the emergence of a superconducting state in topological environments.

The search of new semiconductor materials, for example, A_3B_5 compounds is of great importance for sensor applications. Different interesting effects such as

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Majorana fermions, superconductivity and Kondo effect were observed in topological materials. The interaction between the Kondo effect and Majorana fermions was observed in [4], while the competition be-tween superconductivity and the Kondo effect was shown in [5].

Some works specify the coexisting of partial superconductivity with the Kondo effect in heavily doped n-type GaSb and Bi_2Se_3 whiskers [6, 7]. An anomalous sharp drop of temperature dependencies of resistance was investigated due to the existence of the 2D states in the crystal surface. What is more, the minimum point on the temperature dependences for these samples indicates the existence of Kondo interaction.

According to the results of our previous experiments [8], in which superconductivity occurs in $Pd_xBi_2Se_3$ whiskers. However, in our case, Pd is integrated directly into the Bi_2Se_3 crystal lattice, forming a bulk phase with stable superconducting properties. In $Pd_xBi_2Se_3$ whiskers, we record critical magnetic fields up to 1.45 T, which significantly exceeds the values obtained in [9] (~ 0.25 T) and in [10] (within 0.1-0.3 T, depending on the contact geometry and type of connection). This difference indicates a higher rigidity of the supeconducting state in bulk phases compared to interface or contact implementations. In addition, the presence of a two-step transition in our $Pd_xBi_2Se_3$ samples with $T_{c1} = 5.3$ K and $T_{c2} = 3.5$ K is also unmatched among the aforementioned works, where single-step transitions with lower temperatures are observed. This may indicate a more complex nature of the superconducting phase in our samples, which is likely due to structural heterogeneity, the presence of multiple phases, or a different mechanism for the formation of Cooper pairs [8]. The observed ratio Δ_0/kBT_c significantly exceeds the limit of weakly bound superconductivity, which confirms the involvement of strong electronic correlations. This behavior is characteristic of unconventional superconductors and distinguishes $Pd_xBi_2Se_3$ among most doped systems. The obtained data are consistent with modern theoretical models that predict the possibility of realizing topological superconductivity in Bi_2Se_3-like materials under internal doping conditions.

Our works [7, 8] demonstrate that the integration of Pd into the bulk lattice allows achieving significantly higher critical parameters and more stable properties than in the cases of interface superconductivity. At the same time, similarities in behavior, such as the presence of a fragile superconducting regime at low temperatures, confirm the universal properties of Bi_2Se_3 as a medium for nontrivial superconductivity.

General approach to creating different sensors on the base of ceramic has been given recently in the paper [11]. On the theoretical point of view, this approach is based on the properties of root-polynomial functions, considered in [12]. Obtaining of pure crystals or thin ceramic films on the base of GaSb and Bi_2Se_3 is possible today by using advanced electron beam technologies, based on high-voltage glow discharge electron guns [13].

2. EXPERIMENT

The results of studies using mass ion spectroscopy showed that the concentration of the dopant corresponds to the proximity to the MIT. GaSb whiskers is doped with tellurium $(1\text{-}2.5) \times 10^{18}$ cm^{-3}, and Bi_2Se_3 whiskers is doped with palladium Pd $(1-2) \times 10^{19}$ cm^{-3}.

The *n*-type GaSb and Bi_2Se_3 whiskers were prepared by the method of chemical vapour deposition (CVD) in a closed quartz reactor. Br was the transport agent. Whiskers were doped with Te and Pd to obtain the n-type conductance. The reactor was loaded in a horizontal furnace with a temperature gradient. The diameter of gained whiskers was in the range 20-30 μm, their length approached 1-2 mm. An investigation by the microprobe X-ray analizator (CAMEBAX) allowed determining the concentration of Te and Pd. The electrical contacts were 10 μm in diameter and were made by the welding of a Pt microwire. The conductance type was inspected on the thermo-e.m.f. sing and was confirmed to be *n*-type.

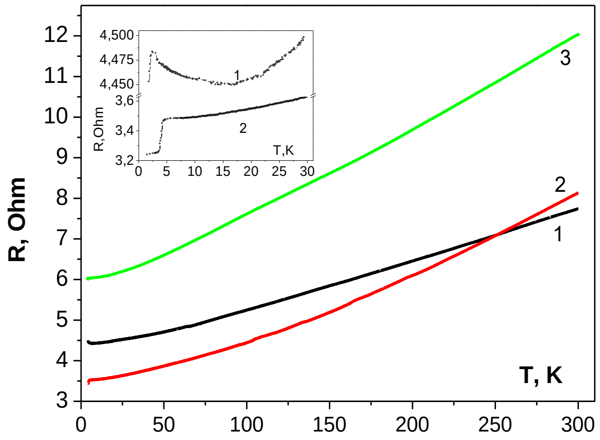
Low-temperature resistance was studied. Crystals were set in a helium cryostat, where they were cooled to temperature 1.5 K. The influence of the magnetic field on the whiskers was investigated by using the Bitter magnet with induction up to 14 T and scanning time of the field 1.75 T/min.

3. RESULTS AND DISCUSSIONS

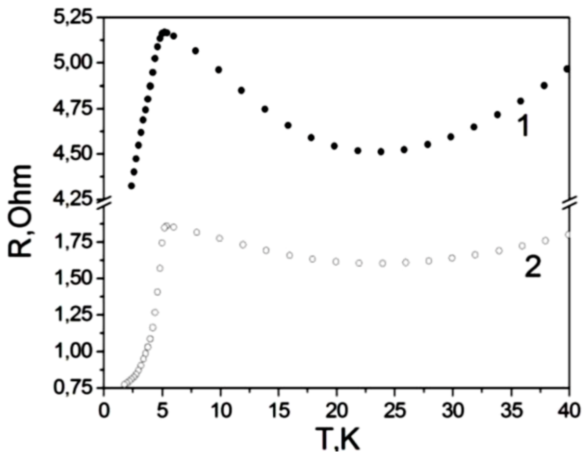
As was mentioned before, *n*-type GaSb and Bi_2Se_3 whiskers with different doping concentrations were studied. Fig. 1, a, b shows their temperature dependences of resistance. Fig. 1a (curve 2) shows the temperature dependences of the resistance of GaSb whiskers with doping concentrations 2×10^{18} cm^{-3} in a zero magnetic field and a temperature range of 1.5 ÷ 300 K. As can be seen from the figure, in this temperature range a decrease in resistance is observed from 8 to 3.5 Ohm, which indicates the metallic conductivity of the studied samples. And at temperatures below 4.2 K, a sharp jump-like drop in the resistance of the samples from 3.5 to 3.25 Ohm was detected. This feature of the behavior of their temperature dependence of resistance is probably due to the transition to a superconducting state at a critical temperature close to the temperature of liquid helium (inset in Fig. 1a (curve 2)). On the other hand, the detected jump in the resistance drop is very small, namely of the order of 8.6 % ((3.5-3.2)/3.5). However, the resistance value of the samples at temperatures below 4.2 K remains large enough, 3.2 Ohm, to be interpreted as a phase transition to a superconducting state, which should be accompanied by a drop in resistance all the way to zero.

A small decrease (8.6 %) at temperatures below 4.2 K in GaSb resistance (inset in Fig. 1a (curve 2)) indicates the formation of small superconducting islands (clusters) in the studied samples, which cause the observed partial transition to the superconducting state. Since the main contribution to the conductivity of GaSb whiskers is believed to be due to surface conductivity, as in InSb [14], it can be assumed that the partial superconductivity should be localized on the surface of the microcrystals. However, if the sample is two-phase (shell-core), the superconducting transition is expected to be somewhat blurred. That is why the narrow transition to the superconducting state obtained by us, in the form of a sharp drop in resistance at a temperature ≤ 4.2 K, can be an additional argument in favor of surface superconductivity of GaSb whiskers.

In GaSb whiskers with a dopant concentration of 2×10^{18} cm^{-3} at a critical temperature of the order of 4.2 K, a partial transition to the superconducting state is likely to occur (inset in Fig. 1a (curve 2)). However, the nature of the manifestation of superconductivity in the studied samples remains unclear, since as the critical temperature $T_c = 1.09$ K for gallium [15, 16], and the Curie temperature for GaSb doped with tellurium are significantly lower [17]. Possible reasons for superconductivity in the studied samples may be their amorphization [18, 19] or a high level of concentration of the dopant Te, close to the critical concentration of MIT, which, as is known, leads to a significant increase in the value of the critical phase transition temperature to the superconducting state T_c [20].



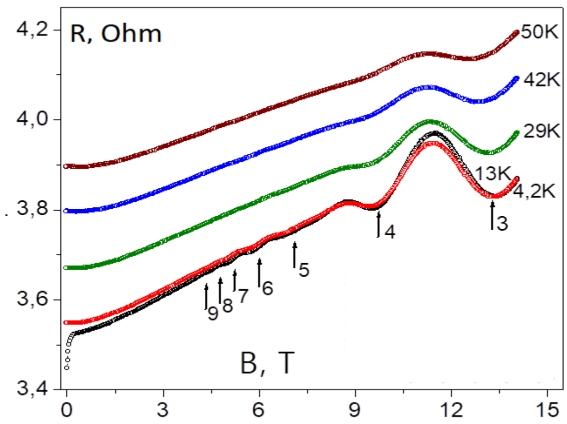
a



b

Fig. 1 – Temperature dependences of resistance for samples in zero magnetic field with different dopant concentrations, cm^{-3}: a) GaSb: 1 – 1×10^{18}; 2 – 2×10^{18}; 3 – $2{,}5 \times 10^{18}$; b) Bi_2Se_3: 1 – 1×10^{19}; 2 – 2×10^{19} Insets: temperature dependences of resistance of these samples at temperatures above 1.5 K

However, amorphization of GaSb whiskers can be excluded, since these samples exhibit Shubnikov-de Haas magnetoresistance (MR) oscillations (Fig. 2), which are usually characteristic of high-quality crystals. According to [6], in GaSb crystals at temperatures close to liquid helium, the metallic phase near the MIT localization threshold may be responsible for the anomalous transition to the superconducting state.



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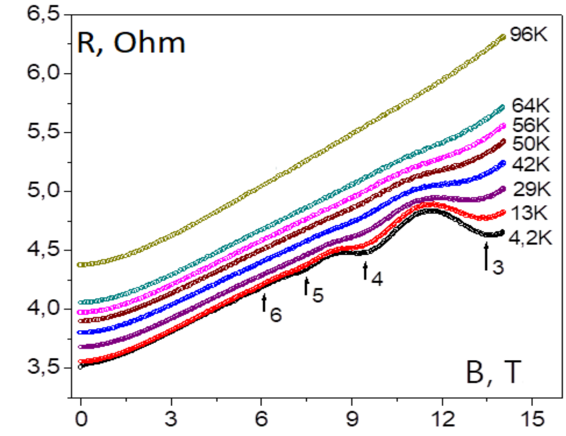


b

Fig. 2 – Field dependences of a) longitudinal and b) transverse MR of GaSb whiskers with a concentration of doping tellurium impurity 2×10^{18} cm^{-3} at fixed temperatures. The arrows indicate the peak numbers of MR oscillations

The peaks of longitudinal and transverse MR were detected at low temperatures in magnetic fields with an induction of $0 \div 14$ T in GaSb whiskers with a doping impurity concentration in the range $(1 \div 2.5) \times 10^{18}$ cm^{-3} (Fig. 2, a, b) which corresponds to the proximity to the MIT [6]. The maximum amplitude of the peaks decreases with increasing temperature in the entire range of fields. The number of transverse MR peaks decreases in comparison with the results presented for GaSb samples in a longitudinal magnetic field at the same temperature. Shubnikov-de Haas oscillations were also detected in our work for *n*-type InSb [14]. The oscillatory effect is observed in GaSb samples with a tellurium concentration of 2×10^{18} cm^{-3} up to temperatures of 50 K (Fig. 2a, b).

The suppression of the superconductivity effect by a magnetic field is also important for a possible explanation of its nature [21, 2]. In order to consider the influence of the magnetic field on the abrupt drop in resistance at a temperature below 4.2 K, it is necessary to study the dependences of the longitudinal MR of GaSb whiskers in the temperature range $1.5 \div 50$ K and magnetic fields $0 \div 14$ T (Fig. 2a). However, the Shubnikov-de Haas oscillations were not detected in the field dependences of the longitudinal and transverse MR of n-type Bi_2Se_3 doped Pd with concentration of $(1-2) \times 10^{19}$ cm^{-3} in magnetic fields of $0 \div 14$ T and low-temperature region 2 – 30 K (Fig. 3).

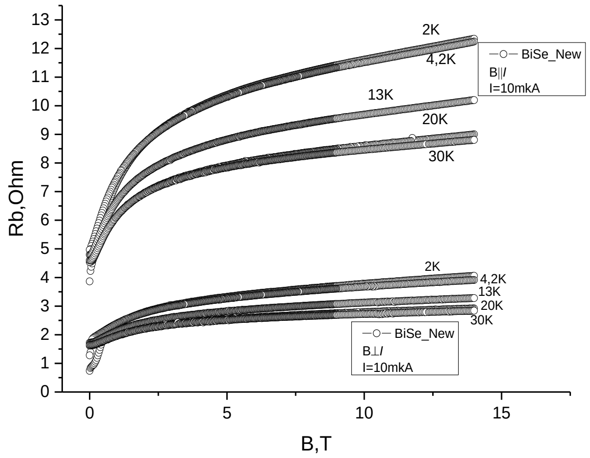
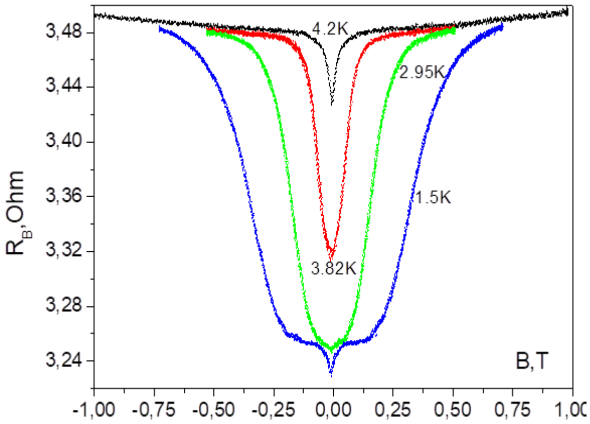


Fig. 3 – Field dependences of the longitudinal and transverse MR of Bi_2Se_3 with a Pd dopant concentration of 2×10^{19} cm^{-3} at fixed temperatures



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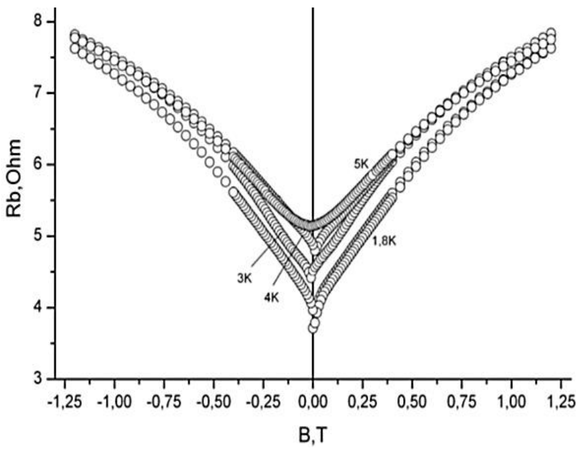
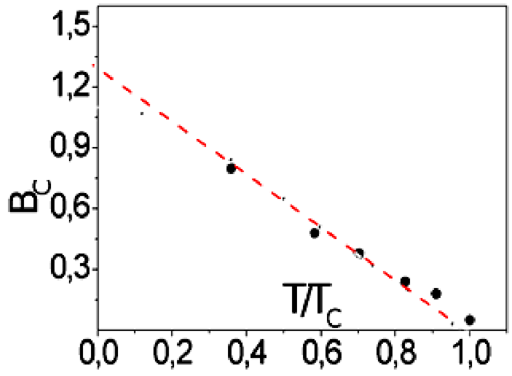


b

Fig. 4 – Field dependences of longitudinal MR at fixed temperatures with different dopant concentrations, cm^{-3}: a) GaSb: 2×10^{18}; b) Bi_2Se_3: 2×10^{19}



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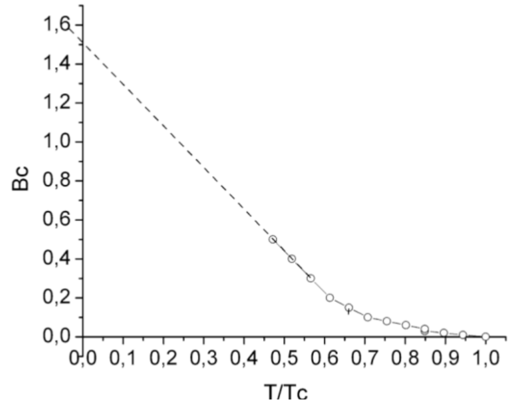

b

Fig. 5 – Critical magnetic field induction for superconductivity in whiskers: a) GaSb; b) Bi_2Se_3. The solid line corresponds to the coincidence of experimental data with the Ginzburg-Landau theory

Another possible reason for the partial superconductivity of GaSb may be the formation of Sb_2Te_3 nanoclusters, which are topological insulators, and the transition to the superconducting state occurs at a critical temperature $T_c = 3$ K [23]. However, Sb_2Te_3 nanoclusters are unlikely to be formed in GaSb whiskers, given the relatively low concentration of tellurium dopant concentration of 2×10^{18} cm^{-3} (according to mass spectroscopy data). As a result, the number of potential Sb_2Te_3 nanoclusters formed is insufficient to provide a superconducting channel. In addition, partial superconductivity in GaSb whiskers doped with tellurium is observed at a critical temperature T_c of the order of 4.2 K (inset in Fig. 1a (curve 2)), which is different from $T_c = 3$ K, characteristic of Sb_2Te_3 nanoclusters.

Let us consider the influence of weak magnetic fields on the resistance of GaSb and Bi_2Se_3 in the region of extremely low temperatures $1.5 \div 5$ K (Fig. 4a, b). The figure demonstrates pronounced sharp jumps in longitudinal MR in the form of so-called bowls or casp at magnetic field induction up to 1.0 T [6].

To have a deeper understanding of the physics associated with the nature of the superconductivity effect, the upper critical magnetic field B_c was determined, obtained from the dependences of the longitudinal MR at fixed temperatures (Fig. 4a, b). The obtained dependence of the critical field B_c as a function of T/T_c is shown in (Fig. 5a, b). The value of the upper critical magnetic field at a temperature of absolute zero $B_c(0)$, obtained by fitting the data to the generalized Ginzburg-Landau model which is shown by the solid curve in Fig. 5, a, b:

$$B_c(T) = \frac{B_c(0)(1-t^2)}{1+t^2} \quad (1)$$

where B_c is critical at temperature T, $t = T/T_c$

It is obvious that the curve $B_c(T)$ (Fig. 5, a, b) exhibits an almost linear dependence in the temperature range 1.5 ÷ 4.2 K, as in the case of topological insulators based on YPtBi [24]. Taking into account this linear dependence (dashed lines in Fig. 5, a, b), by means of a simple extrapolation the value of the upper critical field at zero temperature $B_c(0)$ was obtained, which for GaSb whiskers is 1.3 T and 1.5 T for Bi_2Se_3, respectively.

The value of $B_c(0)$ is significantly lower compared to the Pauli paramagnetic limit for GaSb and for Bi_2Se_3 8.7 T, which suggests a mechanism for breaking superconducting orbital pairs in these crystals [21].

Using the relation:

$$B_c(0) = \frac{\Phi_0}{2\pi\xi(0)^2} \quad (2)$$

where Φ_0 is the flux quantum, the coherence length of the superconductor for GaSb whiskers was obtained as $\xi(0) = 1.7$ nm, which agrees well with the coherence length $\xi_{ab}(0) = 1.0$ nm for cuprates [25]. The coherence length for Bi_2Se_3 whiskers is an order of magnitude higher and is $\xi_{ab}(0) = 15$ nm

Small values of the coherence length ($\xi(0) \sim 1.7$ nm) of Cooper pairs for GaSb whiskers, compared to high-temperature superconductors, can cause a number of interesting effects, in contrast to low-temperature superconductors, which have the same superconducting properties with a value of ξ_0 of the order of several hundred nanometers [25]. Therefore, the obtained small value of the coherence length is evidence of the possible competition of superconductivity with other physical effects in GaSb whiskers [6].

The short coherence length $\xi(0) \sim 15$ nm of Cooper pairs Bi_2Se_3 whiskers is essentially less in comparison with low-T_c materials. On the other hand, the coherence length value for Bi_2Se_3 whiskers can be compared with high-T_c superconductors. That is why; the gained low value of the coherence length shows the coexistence of different extraordinary properties with its superconductivity. A competition between superconductivity and weak localization is possible in Bi_2Se_3 whiskers. The received discrepancy between the upper critical fields obtained from two independent methods (linear approximation and Ginzburg-Landau equation) can divide the MR behaviour on 2 contributions: 1) partial superconductivity; 2) weak antilocalization.

Another possible reason for this behavior of MR in GaSb and Bi_2Se_3 whiskers may be the weak antilocalization effect [6, 8]. The nature of the weak antilocalization effect may be caused by the spin-orbit interaction in the bulk 3D crystal. However, in GaSb whiskers, the two-dimensional nature of electron transport is assumed, as mentioned above, probably originating from surface conduction, as was the case in InSb whiskers [14]

Studies have shown that n-type conductivity GaSb whiskers exhibit anomalies of MR values: the appearance of the NMR in weak magnetic fields at low temperatures. The NMR is due to the fact that the magnetic field allows to order the spins of the charge carriers and, thus, to avoid impurity scattering on the localized state. Weak localization occurs in the temperature range of 1.4 ÷ 1.7 K in GaSb whiskers with a tellurium concentration of 1×10^{18} cm^{-3} and a pronounced semiconductor conductivity (Fig. 6a). As can be seen from the experimental data, the transition to the superconducting state significantly depends on the concentration of doping impurities. Thus, in GaSb with a tellurium concentration of 1×10^{18} cm^{-3}, there is a competition between the Kondo effect and the Cooper interaction (inset in Fig. 1a (curve 1)), similar to the $Pd_xBi_2Se_3$ whiskers studied by us [7]. GaSb whiskers have metallic conductivity, but the concentration of doping impurities is slightly higher than the critical concentration of N_c MIT inherent in this material. As is known, for such samples, part of the charge carriers is localized on the impurities and interacts with free charge carriers, which corresponds to the Kondo interaction, which, together with the thermal interaction, destroys Cooper pairs, and accordingly, leads to the absence of superconductivity at a temperature of 4.2 K.

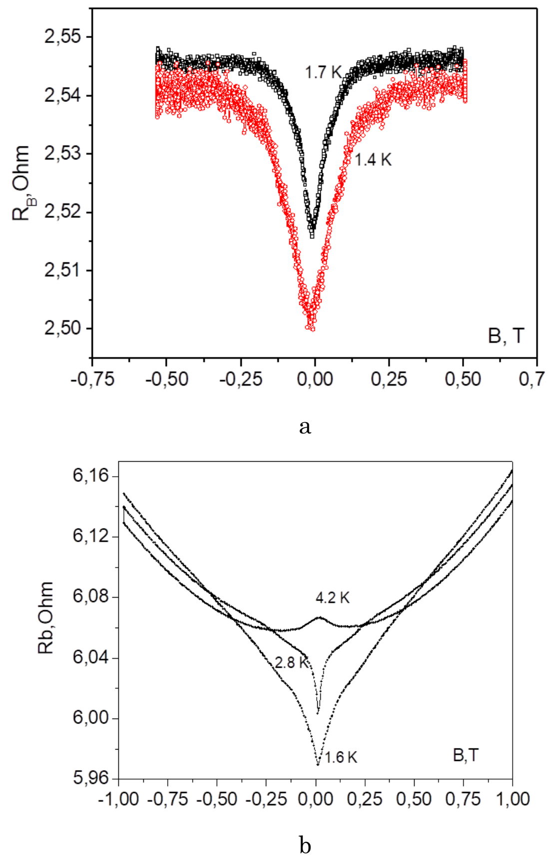

Fig. 6 – Field dependences of the longitudinal MR of GaSb whiskers at fixed temperatures with a tellurium concentration: a) 1×10^{18}; b) $2,5 \times 10^{19}$

So, a significant decrease in the magnetoresistive effect is due to the manifestation of the Kondo effect in GaSb and Bi_2Se_3 whiskers with a doping impurity concentration that corresponds to the immediate proximity to the MIT from the metal side [7].

Studies of MR for GaSb whiskers with a doping impurity concentration of 2.5×10^{18} cm^{-3} confirm this hypothesis. As we can see from the presented experimental values of MR at fixed temperature values presented in Fig. 6b, when the temperature is lowered from 4.2 to 1.6 K, a transition from antilocalization to localization is observed.

At temperatures below 4.2 K, a sudden drop in resistance is observed, indicating the localization of electrons in the crystals. We can assume that the appearance of the NMR is caused by the antilocalization of charge carriers. It is known that in semiconductors and semiconductor structures with two-dimensional (2D) and one-dimensional electron gas (1D) there is no classical MR at low (helium) temperatures. The appearance of a positive MR or NMR depends on the interference of electron waves in the spin-orbit interaction [26, 27]. In particular, the singlet state of interacting electron waves with a total spin $J = 0$ leads to an increase in conductivity (antilocalization effect).

4. CONCLUSION

According to the results of experimental studies in GaSb and Bi_2Se_3 whiskers, it was found that the manifestation of atypical kinetic effects significantly depends on the concentration of the doping impurity.

As a result of studying the temperature dependences of the resistance of GaSb whiskers, doped with tellurium, with a concentration of 2×10^{18} cm^{-3} and Bi_2Se_3 whiskers, doped with Pd to a concentration of 2×10^{19} cm^{-3} in the temperature range of $1.5 \div 5$ K, a sharp drop in resistance was found. It was found that the jump-like drop in resistance on the field dependences of the longitudinal MR of these samples is due to partial near-surface superconductivity. The appearance of superconductivity is due to the strong spin-orbit exchange interaction of charge carriers in the metallic phase in the immediate vicinity of the MIT, which leads to an increase in the Curie temperature.

In GaSb whiskers with a tellurium concentration of 1×10^{18} cm^{-3} and Bi_2Se_3 whiskers with a Pd concentration of 1×10^{19} cm^{-3}, there is a competition between both effects of Kondo interaction and Cooper interaction characteristic of samples with metallic conductivity, in which the concentration of the doping impurity corresponds to the metallic side of the MIT. For such samples, part of the carriers is localized on the impurities and interacts with free charge carriers, leading to Kondo interaction. This interaction, as well as thermal interaction, destroys Cooper pairs and, accordingly, leads to the absence of superconductivity at temperatures higher than 4.2 K and 5.3 K.

At a temperature of 4 K, in heavily doped GaSb whiskers with a Te concentration of 2.5×10^{18} cm^{-3}, a transition from the effect of weak antilocalization to weak localization is established, caused by a change in the ratio between the phase failure time and the spin relaxation time with a change in temperature.

Therefore, weak antilocalization and superconductivity are the main competing mechanisms that probably occur in the near-surface layers, explaining the behaviour of MR dependences in the p-type conductivity of GaSb and Bi_2Se_3 whiskers.

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Близькоповерхнева надпровідність у топологічних ниткоподібних кристалах GaSb і Bi_2Se_3

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Близькоповерхнева надпровідність у топологічно цікавих напівпровідникових ниткоподібних кристалаї, таких як GaSb та Bi_2Se_3, залишається важливою темою для розуміння атипових механізмів спаровування та взаємодії квантових ефектів на нанорівні. Bi_2Se_3 займає особливе місце серед топологічних матеріалів завдяки сильній спін-орбітальній взаємодії та стійким поверхневим станам, що створюють умови для реалізації топологічної надпровідності, здатної підтримувати ферміони Майорани та нові квантові фази. Індукування надпровідності шляхом контрольованого легування або самоорганізованих гетероінтерфейсів відкриває практичний шлях без необхідності застосування високих зовнішніх тисків чи складного епітаксійного нашарування, хоча робочі умови все одно потребують кріогенних температур, характерних для низькотемпературних надпровідників. Никтоподібні кристали GaSb, леговані телуром, і Bi_2Se_3, леговані паладієм, отримані методом хімічного парового осадження та досліджені за температур до 1,5 K у магнітних полях до 14 T. Залежності опору виявили різкий спад нижче 4,2 K для GaSb і нижче 5,3 K для Bi_2Se_3, що свідчить про часткові надпровідні переходи, ймовірно локалізовані поблизу поверхні кристалів. Верхнє критичне магнітне поле $B_c(T)$, отримане з магнітоопорних даних, добре описується моделлю Гінзбурга–Ландау і дає довжини когерентності близько 1,7 нм для GaSb та 15 нм для Bi_2Se_3, що співвідноситься або навіть менше значень, характерних для високотемпературних надпровідників, вказуючи на нетривіальний характер спаровування або посилений вплив спін-орбітальної взаємодії. Наявність коливань Шубнікова–де Гааза у вусиках GaSb підтверджує високу кристалічну якість та виключає аморфізацію як джерело ефекту. Перехід від слабкої антилокалізації до локалізації та чіткі ознаки взаємодії Кондо вказують на конкуренцію між надпровідним спаровуванням і квантовими процесами розсіювання. У легованих вусиках GaSb поблизу порогу метал-ізолятор часткова локалізація носіїв та їх взаємодія з вільними електронами призводить до пригнічення куперівського спаровування при підвищенні температури. Таке співіснування часткової надпровідності, слабкої локалізації та поведінки Кондо демонструє складний баланс конкуруючих електронних кореляцій у цих низьковимірних системах. Отримані результати розширюють розуміння поверхнево-обмеженої надпровідності у топологічних і A_3B_5 напівпровідникових вусиках та створюють основу для інженерії гетероструктур, здатних підтримувати екзотичні надпровідні фази, перспективні для квантових пристроїв.

Ключові слова: Надпровідність, Топологічні ізолятори, Ниткоподібні кристали, Слабка антилокалізація, Ефект Кондо.