Low Temperature Physics/Fizika Nizkikh Temperatur, 2021, vol. 47, No. 1, pp. 24–28

Quantum insulator in a semimetal channel on a single type II broken-gap heterointerface in high magnetic fields

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Received September 23, 2020, published online November 24, 2020

The peculiarity of planar quantum magnetotransport in the type II broken-gap *p*-GaInAsSb/*p*-InAs heterostructures at high magnetic fields has been investigated. The structure of the hybridized energy spectrum of a two-dimensional semimetal channel at a single type II broken-gap heterointerface was considered in dependence on the composition of the quaternary solid solution. A transition from a conducting state to a dielectric state (quantum insulator) for a 2D-semimetal channel at the heteroboundary was observed in quantizing magnetic fields under the condition of simultaneous filling of the first Landau levels for 2D-electron and interface hole states.

Keywords: quantum magnetotransport, seft-consistent quantum wells, type II heterojunction, GaSb, InAs.

Introduction

The general theoretical interpretation of an insulator defines it as a material in which conductivity vanishes at absolute zero temperature. In a classical insulator case, where materials with a forbidden gap are used, it's obvious that the disappearance of conductivity results in an increase in the resistivity. Nevertheless, there are other types of insulators that can exhibit more complex resistance behavior, especially in the presence of a high magnetic field, where different components of the resistivity tensor can exhibit various dependences on the field, for example, the magnetoresistance increases with increasing magnetic field, whereas the transverse (Hall) resistance remains constant [1]. Such systems are called Hall insulators. When a high magnetic field is applied, the effects associated with the transition to the ultra-quantum region, where $\hbar\omega_C \geq E_F$, are easier to observe in metals with a low concentration of current carriers, having relatively low Fermi energies, as well as in semiconductors with a narrow band gap [2]. In the ultra-quantum region, the displacement of the edges of the energy bands can reach a value comparable to the Fermi energy for the forbidden gap of semiconductors. In this case, changes in the energy spectrum of the heterostructure can be observed. The possibility of a transition of semimetals to a semiconducting state in high magnetic fields was predicted by a number of researchers, however, such transition was experimentally observed only for heterostructures with quantum wells or quantum dots filled with one type of charge carriers [3, 4]. In this contribution, we consider the possibility of realizing a semiconductor conductivity mode in a semimetal heterosystem with two types of current carriers in the presence of a high magnetic field. For this purpose semiconductor heterostructures based on antimonide-arsenide compounds with a semimetal channel at a single type II broken-gap heterointerface were chosen as objects of study.

Samples for investigation

The $Ga_{1-x}In_xAs_ySb_{1-y}$ epitaxial layers in the composition range $x = 0.04$–0.2 and $y = x + 0.06$ with a thickness of $d = 1$ μm were grown by liquid-phase epitaxy on compensated *p*-InAs(001):Mn substrates with the excess concentration of holes $p_{77\,\mathrm{K}} \sim 1\cdot10^{14}$ cm^{-3}. The intentional doping of the quaternary solid solution with any acceptor impurity during the epitaxial growth was not performed. The concentration of residual impurities in the undoped p^0-GaInAsSb epitaxial layer did not exceed $p_{77\,\mathrm{K}} \sim 4\cdot10^{16}$ cm^{-3}. A typical energy band diagram of a single type II broken-gap *p*-GaInAsSb/*p*-InAs heterojunction in thermodynamic equilibrium is shown in Fig. 1(a). The studies of quantum magnetotransport in the Hall geometry were carried out in high pulsed magnetic fields up to 35 T at a low temperature $T = 1.5$ K. A drive current was supplied to the samples in both ac and dc mode.

Results and discussion

It's well known that two binary semiconductor compounds with close crystal lattice parameters (for example, GaSb and InAs), as a result of direct contact, can form

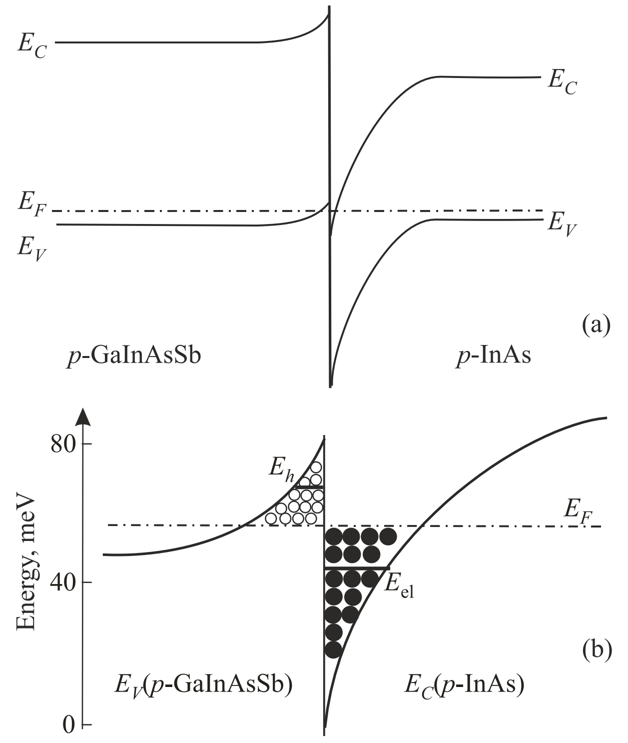

Fig. 1. Schematic energy band diagram of the single type II p-$\mathrm{Ga}_{1-x}\mathrm{In}_x\mathrm{As}_y\mathrm{Sb}_{1-y}$/$p$-InAs heterojunction in thermodynamic equilibrium: (a) common view, (b) electron-hole channel at the single type II p-$\mathrm{Ga}_{1-x}\mathrm{In}_x\mathrm{As}_y\mathrm{Sb}_{1-y}$/$p$-InAs heterointerface with first levels of quantization for electrons (E_{el}, solid circles) and holes (E_h, open circles).

a type II broken-gap heterojunction, where there is an energy overlap at the GaSb/InAs interface between the top of the GaSb valence band and the bottom of the InAs conduction band [5]. To realize an isomorphic heterostructure with minimal deformations and defects at the heteroboundary and in the bulk of the contacting compounds, it is necessary to employ multicomponent $\mathrm{Ga}_{1-x}\mathrm{In}_x\mathrm{Sb}_{1-y}\mathrm{As}_y$ solid solutions [6], lattice-matched with InAs, instead of the binary GaSb, when this heterostructure is obtained on indium arsenide substrates. Recently it was established a composition range of the quaternary solid solution $0 < x < 0.25$, in which the bottom of the conduction band of the InAs matrix continues to be located below the top of the valence band of the GaInAsSb layer [7].

Due to the peculiarity of the pinning of the general level of the chemical potential of the heterostructure within the overlapping region at the p-$\mathrm{Ga}_{1-x}\mathrm{In}_x\mathrm{Sb}_{1-y}\mathrm{As}_y$/$p$-InAs heteroboundary, a semimetal channel for electrons and holes localized in self-consistent quantum wells on opposite sides of the interface is formed in the type II broken-gap heterojunction, as a result of band overlapping at the heterointerface of contacting semiconductors and the flow of charge carriers through the heteroboundary [8]. The total level of the chemical potential of the heterostructure, specified by the degree of doping of the semiconductor compounds forming this heterojunction, is responsible for the position of the Fermi level in the electron-hole channel. Thus, the position of the Fermi level ensures the simultaneous existence of the electron and hole parts of the conducting system at the single type II broken-gap heterojuction. In fact, there is a conducting region (2D electron-hole channel) placed into a semiconductor matrix with a hole-type conductivity [Fig. 1(b)]. The Fermi level in the obtained system was also determined in respect to the conditions of electrical neutrality of the entire heterostructure, which means the semimetal channel is containing an equal number of electrons and holes with finite overlapping of their wave functions across the heterointerface. However, the concentration of electrons and holes is almost equal. In fact, the total concentration of holes is slightly greater than the electron concentration and $n + n_A = p + \delta p$. Excess in the concentration of holes (δp) is determined by a small concentration of ionized acceptors (n_A) in the vicinity of the 2D channel. The conductivity of the semimetal channel with a limited concentration of charge carriers can be associated with the distance of the GaInAsSb valence band from the InAs conduction band. As was established in [7], the energy gap at the heterointerface depends on the composition of the GaInAsSb epilayer and varies in the range of $E_S = 30$–70 meV [Fig. 2(b)]. The observed dependence has

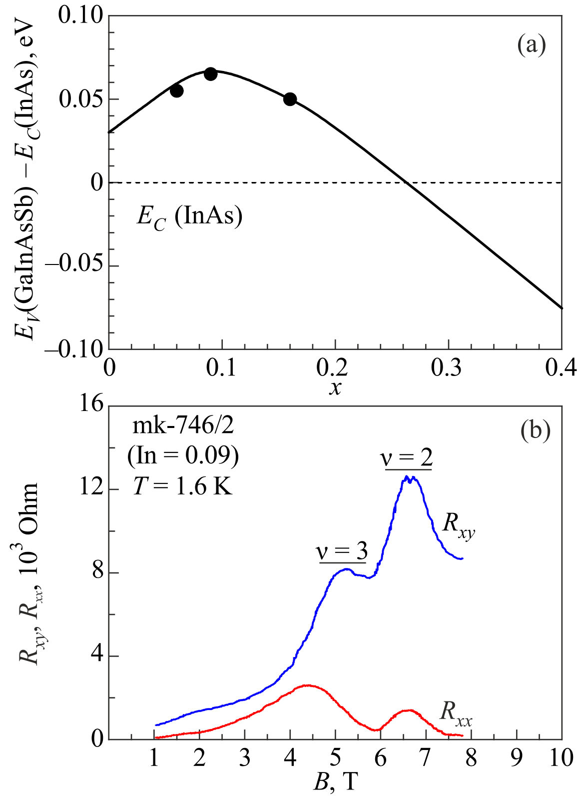

Fig. 2. (a) Energy gap at the single type II p-$\mathrm{Ga}_{1-x}\mathrm{In}_x\mathrm{Sb}_{1-y}\mathrm{As}_y$/$p$-InAs heterointerface in dependence of solid solution composition (dotted line — position of the bottom of the InAs conduction band). (b) Planar magnetotransport in the single type II p-$\mathrm{Ga}_{0.91}\mathrm{In}_{0.09}\mathrm{As}_{0.15}\mathrm{Sb}_{0.85}$/$p$-InAs heterostructure measured at ac mode.

a maximum near the composition $x = 0.09$. Furthermore, as low-field measurements showed 2D electron concentration in the channel corresponding to this composition can get a value of $9{\cdot}10^{11}$ cm^{-2}.

When low magnetic fields ($B < 6$ T) were applied, all samples under study demonstrated a behavior of Hall conductivity determined with a single type of a charge carrier [Fig. 2(b)]. The high value of the Hall mobility [$\mu_H \sim 55000$–70000 cm^2/(V·s)] obtained at $B = 1$ T indicates that the contribution of the "electron" subsystem of the semimetal channel to the total magnetotransport is dominant. It should be noted that the behavior of the dependences of the Hall resistance (R_{xy}) and magnetoresistance (R_{xx}) differ from the "classically" accepted ones with an increase in the magnetic field ($B > 6$ T), namely, the local maxima for R_{xy} do not coincide with the local minima for R_{xx}. In the range of middle magnetic fields ($6 \text{ T} < B < 10$ T), a dip in the Hall resistance dependence was observed that manifests of a significant impact of the "hole" subsystem to the total resistance of the heterostructure. The contribution of holes localized in one dimension in the potential well on the side of the quaternary solid solution to planar magnetotransport can be expressed as a finite nonzero value of the R_{xx} component whereas the local maximum for R_{xy} component was achieved. Thus, plateaus of the integer quantum Hall effect for two-dimensional electrons from the semimetal channel were observed against the background of the hole subsystem. Moreover, in the range of middle magnetic fields, starting from $B = 8$ T, a manifestation of in-phase (synchronous) trend in the magnetotransport component curves was found out. It indicates the simultaneous participation of both the electron and hole quantized subbands in the magnetotransport of the heterostructure. Therefore, the value of the total filling factor in the range of magnetic fields $10 \text{ T} < B < 15$ T will be different from the value $\nu = 2$, and may even exceed it.

Recently, we have calculated a fan diagram of Landau levels for a semimetal channel at a single type II broken-gap p-Ga$_{0.91}$In$_{0.09}$Sb$_{0.16}$As$_{0.84}$/p-InAs heterointerface [9]. The fan diagrams [Figs. 3(b), 4(b), and 5(b)] of the two-component (electron-hole) system in the magnetic field are calculated in the approximation of noninteracting particles. The proposed model takes into account the assumption that the quantum wells for electrons and holes can be presented

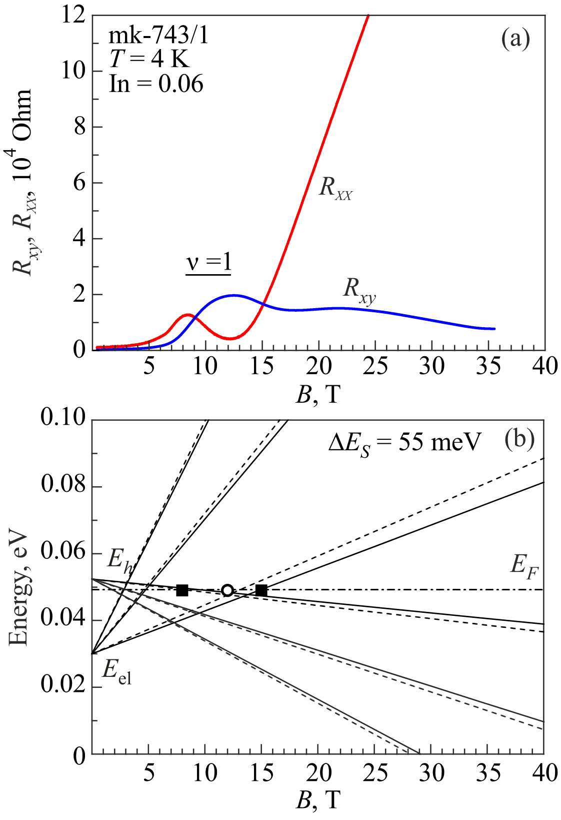

Fig. 3. (a) Quantum magnetotransport in the single type II p-Ga$_{0.94}$In$_{0.06}$As$_{0.13}$Sb$_{0.87}$/p-InAs heterostructure measured at dc mode. (b) Landau fan diagram at the single type II p-Ga$_{0.94}$In$_{0.06}$As$_{0.13}$Sb$_{0.87}$/p-InAs heterointerface in the magnetic field with extreme points of magnetoresistance (local maxima — solid squares, local minima — open circles). E_F is the position of the Fermi level of the heterostructure. $E_{\rm el}$ and E_h are the ground state energies of electrons and holes in their quantum wells.

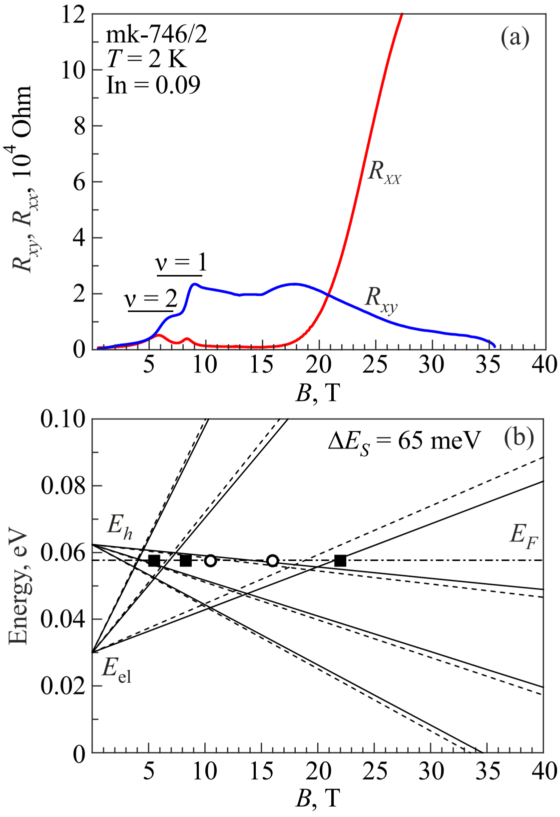

Fig. 4. (a) Quantum magnetotransport in the single type II p-Ga$_{0.91}$In$_{0.09}$As$_{0.15}$Sb$_{0.85}$/p-InAs heterostructure measured at dc mode. (b) Landau fan diagram at the single type II p-Ga$_{0.91}$In$_{0.09}$As$_{0.15}$Sb$_{0.85}$/p-InAs heterointerface in the magnetic field with extreme points of magnetoresistance (local maxima — solid squares, local minima — open circles). E_F is the position of the Fermi level of the heterostructure. $E_{\rm el}$ and E_h are the ground state energies of electrons and holes in their quantum wells.

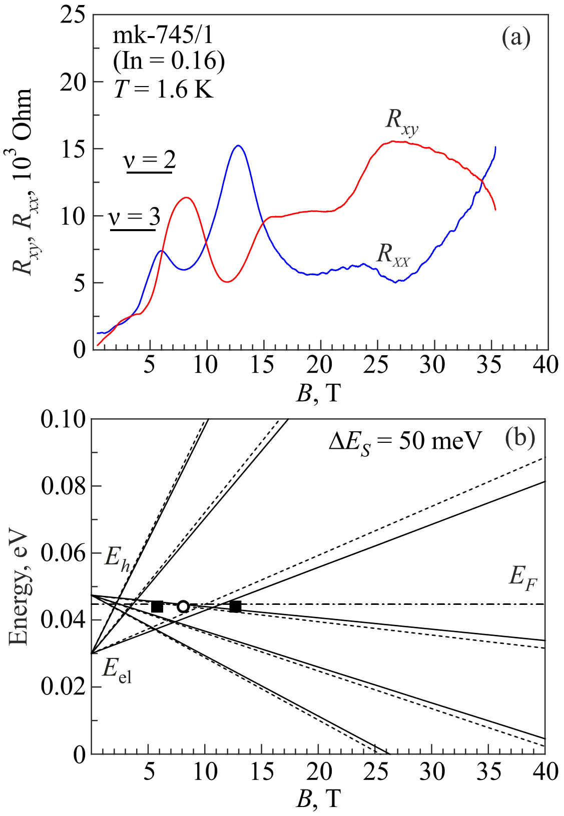

Fig. 5. (a) Quantum magnetotransport in the single type II p-$Ga_{0.84}In_{0.16}As_{0.22}Sb_{0.78}$/$p$-InAs heterostructure measured at dc mode. (b) Landau fan diagram at the single type II p-$Ga_{0.84}In_{0.16}As_{0.22}Sb_{0.78}$/$p$-InAs heterointerface in the magnetic field with extreme points of magnetoresistance (local maxima — solid squares, local minima — open circles). E_F is the position of the Fermi level of the heterostructure. E_{el} and E_h are the ground state energies of electrons and holes in their quantum wells.

as a triangular shape and the quantization of heavy holes in a magnetic field had occurred. Electrons were trapped in the triangular quantum well on InAs side of the heterointerface. Heavy holes were trapped in the triangular quantum well on the other side of the heterointerface. The estimated first energy levels are ~ 30 meV for electrons and ~ 2.6 meV for holes, and we assume that they do not depend on the interface energy gap (E_S). It should be noted that energy levels were measured from the bottom of the InAs conduction band at the heteroboundary. The following parameters were used in calculations: $m_e = 0.04\, m_0$ is an effective electron mass in InAs; $m_{hh} = 0.15 m_0$ is an effective heavy hole mass; the absolute value of g factors is 3.1 for electrons, and 1 for holes. The Fermi level in the semimetal channel was self-consistently calculated from the condition that the electron and hole concentrations are equal $n = p$ at $B = 0$. The interface energy gap (E_S) shifts the position of quantized energies for holes relative to the bottom of the InAs conduction band. Thus, the concentration of electrons and holes in the channel changes depending on the gap E_S.

When a magnetic field is applied, the spin degeneracy of the Landau levels is eliminated and each level splits into two sublevels. As the total Fermi level of the whole heterostructure is hold by the doped bulk of contacting materials, a crossing of Landau levels with the level of chemical potential at the magnetic field increasing results in revealing of features in magnetotransport.

Now let’s analyze the features of the planar magnetotransport in the type II broken-gap p-$Ga_{1-x}In_xSb_{1-y}As_y$/p-InAs heterojunction in high magnetic fields ($B > 15$ T) using the proposed model. Three quaternary solid solutions from the compositions range $0 < x < 0.2$ were selected according to the dependence of the interface energy gap (E_S) shown in Fig. 2(a): $x = 0.09$ as a maximum value of E_S and $x = 0.06$ and $x = 0.16$, which are located on the curve on opposite sides of the maximum. Figures 3–5 reflect the results of magnetotransport study and calculation of the Landau fan diagram for each composition of the GaInAsSb epilayer, respectively. Extreme points (minima and maxima) of the magnetoresistance field dependence were extracted from graphs named as (a), and then those data were superimposed to Landau fan diagram (b). Figures show that the magnetoresistance minima were placed sufficiently close to points of intercrossing of Fermi level and Landau levels, whereas the magnetoresistance maxima were found out as a little bit remote from those. From the comparison analysis of maxima points of magnetoresistance got at highest magnetic fields, it can be concluded that they are situated in a region where lowest (0+,–) Landau levels (both for electrons and holes) have escaped from below the Fermi level with an increase in the magnetic field. Consequently, the conductivity of a semimetal channel at the heterointerface can achieve a semi-insulator state.

In accordance with theoretical calculations, the transition called “quantum Hall effect–quantum insulator” occurs in high magnetic fields, where the plateau on the dependence of the Hall resistance corresponds to a filling factor close to ν = 1 [10]. The possible deviations from this value can be explained by the strong spatial inhomogeneity of the system, in which the current flows through the grid of conducting channels formed by regions of other types of charge carriers [4]. It should be noted that in both reports the 2D channels contained only one type of charge carriers (electrons) in contrary to our case. In turn, the magnetoresistance and the Hall resistance of a two-carrier 2D system in a high magnetic field can demonstrate complicated behavior due to the possibility of electron-hole recombination near the edges of the semimetal channel [11, 12]. Annihilation of electrons and holes occurs in high magnetic fields due to equalization of their Hall mobility taking into account of an equal number of them in the semimetal channel. The small excess of hole concentration (δp) results in the nonmonotonic field dependence of the magnetoresistance and decreasing of the Hall resistance in high magnetic fields [see Figs. 3(a) and 4(a)] as predictted elsewhere [12]. Depending on the composition of the quaternary solid solution, and, consequently, on the width of the gap at the heterointerface in the area of the energy bands overlapping and concentration of charge carriers in the semimetal channel, the critical value of the magnetic field, where "semi-insulator" state can be obtained, will be different. The total concentration of electrons and holes in the samples with the small interface gap E_S = 50 meV is not enough to satisfy the quantization conditions in contrary to the cases mentioned above, so the quantum Hall insulator regime cannot be achieved [Fig. 5(a)]. It can be attributed to the increasing role of electron-electron interaction in the 2D system at the interface due to the lower concentration of carriers in the semimetal channel [13]. With a further increase in the magnetic field, the manifestation of hopping conductivity can be realized.

Conclusions

A semimetal channel for electrons and holes localized in self-consistent quantum wells on opposite sides of the interface is formed in the type II broken-gap heterojunction, as a result of band overlapping at the heterointerface of contacting semiconductors and the flow of charge carriers through the heteroboundary. A transition from a conducting state of the 2D metal to a dielectric state (quantum insulator) was observed in quantizing magnetic fields as a result of leaving the lowest Landau levels above the Fermi level in the system for both electrons and holes. The escape of the lowest Landau level for the "electron" subband from below the Fermi level can lead to hopping conduction through localized states, which are caused by the potential inhomogeneity at the heterointerface.

Acknowledgments

This research has been partially funded by the Russian Science Foundation project No. 17-12-01182c (theory) and has been partially supported by Program No. 9 of the Presidium of the Russian Academy of Sciences, entitled "Terahertz Optoelectronics and Spintronics".

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Квантовий ізолятор в напівметалевому каналі на одинарному розривному гетероінтерфейсі II типу в сильних магнітних полях

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Досліджено особливість планарного квантового магнітотранспорта в розривних гетероструктурах II типу *p*-GaInAsSb/*p*-InAs в сильних магнітних полях. Розглянуто структуру гібридизованого енергетичного спектра двовимірного напівметалевого каналу на одинарному розривному гетероінтерфейсі II типу в залежності від складу чотирьохкомпонентного твердого розчину. Перехід з провідного стану в діелектричний (квантовий ізолятор) для 2D-напівметалевого каналу на гетероінтерфейсі спостерігався в магнітних полях за умови одночасного заповнення перших рівнів Ландау для двовимірних електронних та інтерфейсних діркових станів.

Ключові слова: квантовий магнітотранспорт, самоузгоджені квантові ями, гетероконтакт II типу, GaSb, InAs.