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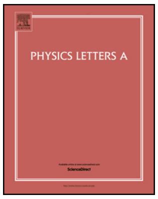

Magnetoresistance peculiarities of bismuth wires in high magnetic field

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ABSTRACT

Magnetoresistance measurements of Bi wires performed in the magnetic field oriented along the bisector axis revealed unexpected anomalous peaks in a high magnetic field far above the quantum limit of the electrons. By combining a magnetic field and an uniaxial strain, we obtained a modification of the electronic structure; as a result, the quantum limit for light and heavy electrons is changed in a different way. For the case where heavy electrons are in the quantum limit, a correlation between the exit of the lowest Landau level of light electrons and the Lifshitz transition was found.

1. Introduction

The present work was motivated by the previous observations of the variety of unexpected anomalous features manifested in bulk Bi in an ultraquantum magnetic field. The electronic structure of bismuth can be modified under the action of a high magnetic field, where various kinds of magnetic-field-induced instabilities may occur. Low densities of electrons combined with their small effective masses and a small energy overlap are strongly affected under a magnetic field that gives rise to significant changes in the Fermi surface topology and in the dependence of the carrier density on magnetic field. In high magnetic fields, the band overlap diminishes and a magnetic-field-induced semimetal–semiconductor transition [1] is observed at 88 T. In the field where the energy overlap becomes small and approaches zero, the occurrence of various types of magnetic-field-induced phenomena is anticipated [2].

In relatively high magnetic fields, where all Landau levels (LLs), except for the lowest Landau level (LLL), have passed through the Fermi energy level, the so-called quantum limit (QL) is achieved. A low carrier density in bulk Bi allows attaining a QL for all carriers in a moderate magnetic field. For example, if the magnetic field is oriented along the trigonal axis, both electrons and holes can be placed into the LLL below 9 T. Therefore, we would not expect any features in the transport properties of the carriers in a magnetic field above 9 T. Nevertheless, a lot of unexpected effects were experimentally detected in bulk Bi well beyond the QL, namely in the case where the magnetic field is oriented along the trigonal axis or close to it [3–12]. The measurements of the Nernst response in bismuth revealed giant quantum oscillations and unknown peaks up to a magnetic field of 33 T [4,8]. Furthermore, anomalous peaks were observed even in higher magnetic fields of up to 50 T [8,9]. The unidentified peaks found by Behnia [4], initially were associated with fractional peaks as signature of electron fractionalization possible for bulk Bi in a high magnetic field. Further, Zhu et al. [6] suggesting the twinning scenario, concluded that the unidentified peaks found by Behnia are not fractional peaks as was initially assumed [4]; instead, those peaks originate from the crossing of the Fermi energy level by the LLs of holes from a secondary twined crystal. In the conclusions, the authors of [6] left an open question: why the magnitude of the unidentified peaks caused by the LLs of secondary twined crystal is comparable to those of the primary crystal? This question was raised again [7] at an attempt to explain the observed angular asymmetries in the magnetostriction measurements where the authors have failed to detect traces of secondary twined crystal. The following investigations [3,7,10] have revealed new nuances in the behavior of bulk Bi in the magnetic field which could no longer be explained in the terms of non-interacting model. Performed measurements of angular-dependent magnetoresistance [3] have shown a high sensitivity of the flow

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of electrons along the trigonal axis to the orientation of a rotating perpendicular magnetic field. In the same article [3], the authors have put forward the idea that the observed spontaneous loss of a threefold valley degeneracy with decreasing temperature and/or increasing magnetic field may be an experimental manifestation of the valley-nematic Fermi liquid state [9]. This idea has been involved and developed in [7] for the explanation of a spontaneous symmetry breaking found in the magnetostriction measurements. The observed threefold symmetry breaking in magnetoresistance [3] and magnetostriction measurements [7] point to a different density of states (DOS) of electrons at the Fermi energy level presumably due by the electron interaction which operates selective between the identical valleys for magnetic fields along the trigonal axis. A similar evidence of a different DOS was found [10] in measurements of the Shubnikov–de Haas (SdH) oscillations at the rotation of a magnetic field around the trigonal axis that revealed the difference in the amplitude of oscillations from the three identical electron valleys. To justify the emergence of a different DOS, in the last mentioned papers [3,7,10] sophisticated theoretical arguments have been advanced including a quantifying of the components of the mobility tensor, a selective Coulomb interaction and scenario of valley nematicity, which are beyond the framework of the single particle model.

Another interpretation of the unusual peaks observed in the Nernst effect of bulk bismuth has been recently proposed by Mikitik and Sharlai [11]. Their explanation is based on the effect of the spontaneous symmetry breaking which is caused by the electron–phonon interaction inducing the magnetostriction. As a result, a first-order phase transition can take place in certain intervals of magnetic fields when LLs of equivalent electron pockets approach the Fermi energy. This situation occurs in high magnetic fields ($H > 9$ T) oriented along the trigonal axis where the LLL of electrons 0^-(e) is filled, while the next LLL 0^+(e) is close to the Fermi energy level and could cross it. Further, the authors admit the possibility of spontaneous symmetry breaking of two equivalent electron ellipsoids in the case of the magnetic field oriented along the bisectrix direction. The last assumption will guide the discussion of our results in this context.

The origin of most of the observed Nernst peaks above the QL has been explained [13] in terms of the two-band model advanced by Smith, Baraff, and Rowell [14]. According to the conclusions in [13], this simple model is sufficient to account for the general shape of some experimental curves when the magnetic field is along or close to the trigonal axis. An extended interpretation of unknown Nernst peaks for the different magnetic field orientations was given in the detailed calculations in Ref. [5].

Another advanced idea [15] of the responsibility of the surface states for anomalous high-field peaks has been convincingly denied by K. Behnia [16] in his detailed analysis of the Nernst experiment in bulk Bi. A similar assumption [17] that high field features of bismuth are related to the electronic properties of the surface states refers to the Bi nanowires with $d = 90$ nm. Results of the investigations [17] of the effect of strong Rashba spin–orbit coupling on the superconducting proximity assume the existence of the surface channels that manifest specific conduction properties oscillating in a magnetic fields up to 11 T for thin Bi nanowires ($d < 100$ nm) with superconducting contacts. To date, however, there has been no reliable experimental evidence of the surface states in Bi wires, while there is the problem of correct separation of the effects originating from bulk or from surface of the wires.

In the cases where the magnetic field is oriented along the bisector direction, the QL for both light and heavy electrons is attained in a magnetic field less than 2.5 T, while the heavy T-holes remain in the quasi-classical regime. Some interesting features manifested in the magnetoresistance (MR) dependence in this field direction were observed in the previous experiments performed in a magnetic field of up to 40 T reported by Brandt [2] and Hiruma [18]. In those earlier experiments [2,18] on bulk Bi in a magnetic field oriented along the bisector and/or binary axis, the dependence of magnetoresistance exhibited a broad peak followed by a sharp decrease in the MR in a magnetic field of 32 T. Based on the "camel-back" structure in the $k(H)$ dependence of light electrons (k is the wave vector component in the direction of the magnetic field) proposed by Vecchi et al. [19], it was supposed that the peak observed at 32 T can be attributed to the crossing of the Fermi energy level by the LLL of light electrons [18]. More recently, results on the MR and Nernst effect [5,8], as well as the important theoretical calculations for a field oriented along different crystallographic directions [3,10–13,19–22], have been reported.

In general, the variety of unexpected features [4–12] manifested in an ultraquantum magnetic field in the bulk Bi may not always be explained in terms of simple models. These complexities suggested that the band structure of bulk Bi becomes so intricate in a high magnetic field that, for any suitable explanation, we should take into account many factors including the enhancement of the interaction effect and its influence on the LL spectrum in the vicinity of the QL. In all instances, a plurality of observed phenomena beyond the QL, which cannot always be understood in the framework of the known models, requires new theoretical developments and inspires the expansion of experiments on bismuth in a high magnetic field.

Most of the published results have respect to experiments on bulk Bi that differ only in the configuration of the experiment with the different orientations of the magnetic field relative to the crystallographic axis and/or in the magnetic field range. At the same time, in addition to magnetic fields, the band structure of Bi is sensitive to other external influences. However, the design of measurements in a magnetic field may be diversified by using an additional external influencing factor, for example, uniaxial deformation.

It is well known that even a small lattice deformation leads to substantial changes in the energy spectrum and, accordingly, in values of kinetic parameters of electrons and holes [23]. It has been shown that deformation along some crystallographic directions in Bi can easily induce an Electronic Topological Transition (ETT), which is also referred to as a 2.5 Lifshitz transition [24]. Beyond the interesting effects caused by the Lifshitz transition in bulk Bi [25], there are similar effects in the transport properties of Bi whiskers [26] and Bi wires [27,28]. The glass-coated Bi wires support strong elastic deformations up to the extension $\varepsilon = 3.0\%$. Our earlier investigations of the galvanomagnetic transport properties in uniaxially strained wires have revealed a non-monotonous behavior of electrical resistance and the sign change from positive to negative in the Seebeck coefficient for the Bi wires undergoing the Lifshitz transition of the Fermi surface [28].

Application of an uniaxial deformation directed along the bisectrix axis provides the occurrence of selective changes in the band overlap between T-holes and light electrons and between T-holes and heavy electron ellipsoids, which can be monitored by means of the SdH oscillations. It should be noted that the uniaxial strain in Bi wires contributes to an increase in the band overlap between pockets of heavy L-electrons and T-holes, in contrast to a decrease in this parameter under the action of a magnetic field.

The goal of this work was to study the transport properties of Bi wires under the simultaneous action of a uniaxial deformation and a magnetic field oriented along the bisectrix axis. By combining a high magnetic field and a strain, we have obtained a modification of the electronic structure of the wires; as a result, the QL for light and heavy electrons could be changed in different ways. For the case where heavy electrons are in the QL, a correlation between the exit of the LLL of light electrons and the Lifshitz transition was found. The result is that the critical magnetic field of the

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