

ANOMALIES IN MAGNETORESISTANCE OF BISMUTH WIRES IN HIGH MAGNETIC FIELDS

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(Received December 1, 2015)

Abstract

Anomalous peaks in the magnetoresistance of Bi wires have been observed in a high magnetic field far above the quantum limit of the electrons. By combining a magnetic field and a uniaxial strain, we have obtained a modification of the electronic structure; as a result, the quantum limit for light and heavy electrons has changed in a different way. The origin of anomalous peaks is attributed to the complexity of the structure of the lowest Landau level of heavy electron pockets in a high magnetic field.

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, 3].

In relatively high magnetic fields, where all Landau levels (LLs), except for the lowest Landau level (LLL), have passed through the Fermi 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 [4–12]. 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 a spontaneous symmetry breaking observed in the magnetostriction measurements where the authors have failed to detect traces of secondary twined crystal. In the same article, the authors put forward the idea that the observed angular asymmetries of magnetostriction 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 [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 [4–6] 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 for the different magnetic field orientations.

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. Another 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, 9], as well as the important theoretical calculations for a field oriented along different crystallographic directions [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 a 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 ETT has decreased and, consequently, the magnetic field range of occurrence of magnetic-field-induced instabilities in the electron–hole system has been extended.

2. Experimental results and discussion

Investigated single-crystalline Bi wires were obtained using the glass-coated melt spinning method [29]. The axis of the prepared wires is oriented at an angle of about 19° to the C_1 bisector axis in the bisector–trigonal plane. Experimental procedure and methods are described in detail in our previous papers related to the galvanomagnetic properties of Bi wires [28, 30]. In the given work we consider the results of measurements in the magnetic field extended up to 35 T and focus on the explanation of the unusual features of magnetoresistance in a high magnetic field.

The measurements of longitudinal MR ($I \parallel B$) were made on Bi wires with diameters of $d = 0.2 - 2.0 \mu\text{m}$ in a magnetic field parallel to the axis of the wire, i.e., close to the bisector axis. Figure 1 presents the dependence of the longitudinal MR for a wire with $d = 400 \text{ nm}$ in the pulsed magnetic field of up to 35 T. The non-monotonic field dependence of MR in the range of low magnetic field (up to 10 T) is similar to that reported previously for Bi wires [31]. In accordance with the Chambers theory [32] the longitudinal MR achieves its maximum, and after B_{max} , starts decreasing due to decrease in the carrier-surface scattering. The SdH oscillations are observed as the resistance maxima: weak oscillations from electrons in a low magnetic field and more visible from holes in a high magnetic field. The QL achieved for all electrons at magnetic field above $\sim 3 \text{ T}$ is followed by the negative MR range with an increase between 7 and 35 T.

Some instabilities evident as weak oscillations (wiggles) were observed in a magnetic field around 15 and 20 T. The most prominent feature of MR in a higher magnetic field is the presence of a sharp peak at 33 T. The magnitude of the unexpected peak is larger than that due to the SdH oscillations from holes and even than that due to the crossing of the Fermi level by the first Landau level of electrons in the QL. At the first glance, one can assume that the observed unusual features may be an indicator of unknown effects. On the other hand, the possible unexpected changes in the energy spectrum in the given field orientation may give the appearance of the anomalies in the transport properties that can nevertheless be understood in terms of well-known models of the band structure in bulk Bi.

In order to explain the origin of the observed unusual features of the MR dependence presented in Fig. 1, we will analyze the evolution of the energy spectrum with the magnetic field oriented along the bisector axis. From the well-established band structure [33] of bulk Bi, it is known that the transport in the bisector direction is provided by three groups of carriers: holes from the T-ellipsoid, light electrons from the ellipsoid (A) elongated along the bisectrix axis, and heavy electrons from the two ellipsoids (noted as B and C) placed symmetrically relative to the bisector axis.

In order to verify the contribution of different groups of carriers to the electrical conductivity in Bi wires, we conducted the Fourier analysis of SdH oscillations on the MR measurements using a slow sweep of the magnetic field in the Bitter magnet of up to 14 T. Quantum oscillations from three groups of carriers are visible on the derivative dependence of resistance dR/dB as a function of $1/B$. The calculated frequency of SdH oscillations for the heavy electrons from two equivalent ellipsoids is $F_{B,C} = 2.7 \text{ T}$; for light electrons, $F_A = 1.3 \text{ T}$; and for T-holes, $F_h = 16.1 \text{ T}$, which is in agreement with data for bulk Bi crystals oriented at an angle of about 19° with the bisector axis in the bisector–trigonal plane.

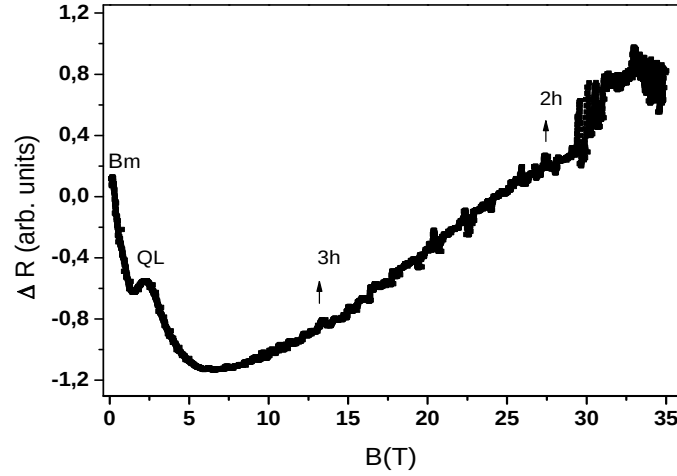


Fig. 1. Longitudinal magnetoresistance for Bi wire with $d = 400$ nm in a magnetic field up to 35 T at $T = 4.2$ K. Arrows indicate: QL_e is quantum limit of electrons, 2_h and 3_h are indexed as peaks of quantum oscillations from holes, B_{max} is the Chambers maxim.

To better understand the behavior of the MR dependences, we should trace the change in the carrier concentrations with increasing magnetic field oriented along the bisector axis. Unfortunately, we have not found any references with theoretical calculations on a variation in the carrier density in a high magnetic field in the bisector direction, except for the presented detailed calculations [5] for all the carriers, however, only up to 12 T; and Landau spectrum only for holes [6] up to 30 T.

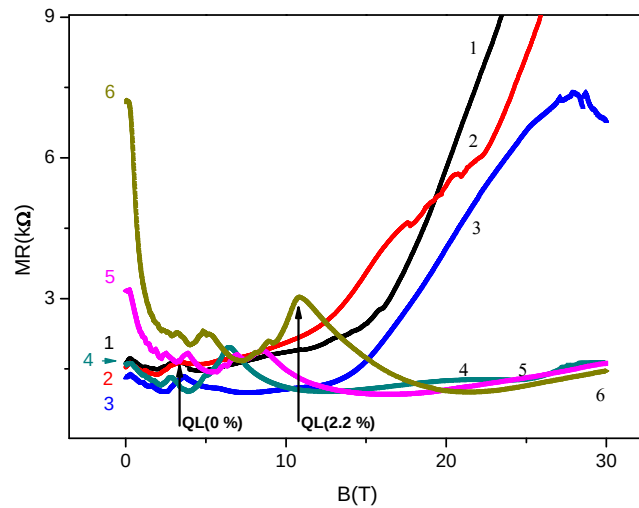


Fig. 2. Magnetoresistance for a Bi wire with $d = 400$ nm at various strain values: (1) 0, (2) 0.4, (3) 0.8, (4) 1.4, (5) 1.8, and (6) 2.2% at $T = 4.2$ K. The vertical arrows indicate the position of the QL_e of heavy electrons that shifts to high magnetic field: arrow $QL(0)$ in the non-deformed state and $QL(2.2)$ at a strain value of 2.2%. Inset: expanded version of the MR in a low magnetic field.

Figure 2 shows the data on the longitudinal MR for a wire with $d = 400$ nm for different uniaxial strain values at a temperature of 4.2 K measured in a resistive magnet of up to 30 T. In a non-deformed state of the wire (curve 1, Fig. 2), the MR dependence is similar to that of the MR measured in a pulsed magnetic field up to 35 T (Fig. 1). The resistance dependence on strain in the absence of a magnetic field represents a nonmonotonic curve.

3. Discussion

In the following we analyze the observed instabilities evident as weak oscillations (wiggles) of MR manifested in a magnetic field range of 14–16 T. The strain leads to a shift of MR wiggles-instabilities to higher magnetic fields (curves 1–3 in Fig. 2; Figs. 3b–3d). Although these oscillating instabilities are obscured by the increasing background resistance in Fig. 2, they are clearly seen in the MR derivative, as shown in Fig. 3b. Close examination of the derivative dependence dR/dB more distinctly reveals the wiggles around 15 T followed by an unidentified peak indexed as X with a positive sign of the jump in the magnetic field range between 3h and 2h hole peaks (arrow X in Fig. 3b) and with a negative sign of the jump in the MTEP dependence (arrow X in Fig. 3a) in a magnetic field of 19.5 T. According to the Fourier analysis of the MR curves, the QL has already been achieved for all the electrons in a field of $B = 2.7$ T; only heavy T-holes remain in the quasi-classical regime; however, the period of the SdH oscillations from T-holes is not compatible (too large) to fit with the observed oscillating instabilities and with the unidentified peak X. The peak with a negative jump on the MTEP dependence (Fig. 3a) could be regarded as a simple minimum between 3h and 2h hole peaks. However, there are two reasons for opposing this assumption: (i) the peak is so deep that leads to a change in the sign of Seebeck coefficient at a magnetic field of 19.5 T and (ii) the displacement of its position in the magnetic field does not correlate with a decreasing period of quantum oscillations from holes under strain. Therefore, we can unambiguously claim that the wiggles and the anomalous jump in a magnetic field range of 15–20 T may not be attributed to the crossing of Fermi level by the LLs of the holes, which are still in the quasi-classical regime of magnetic field.

As was noted in introduction, to explain the variety of previously detected anomalies of electronic properties in a magnetic field above the QL, in the previous reports [4–22], theoretical models with different approaches—ranging from a simple non-interacting band picture to correlation effects that would lead to the exotic states in bulk Bi—have been invoked.

The possibility of appearance of unexpected features above the QL of electrons was confirmed by theoretical calculations [21] in terms of a tight-binding model appropriate for bismuth, where unconventional Zeeman splitting diminishes the separation between the LLL and the second LL and strongly suppresses the electron QL. Similar conclusions have been made in [13], where the origin of the unidentified peaks in the Nernst coefficient has been explained in terms of a simple model of the electron energy spectrum of bismuth advanced by Smith, Baraff, and Rowell [14]. The computed angular dependences [13] of the positions of electron peaks 0^+ , 1^- , and 1^+ in the trigonal–bisector plane is of interest because our measurements were performed with a magnetic field oriented at an angle of 70° to the trigonal axis in the bisector–trigonal plane.

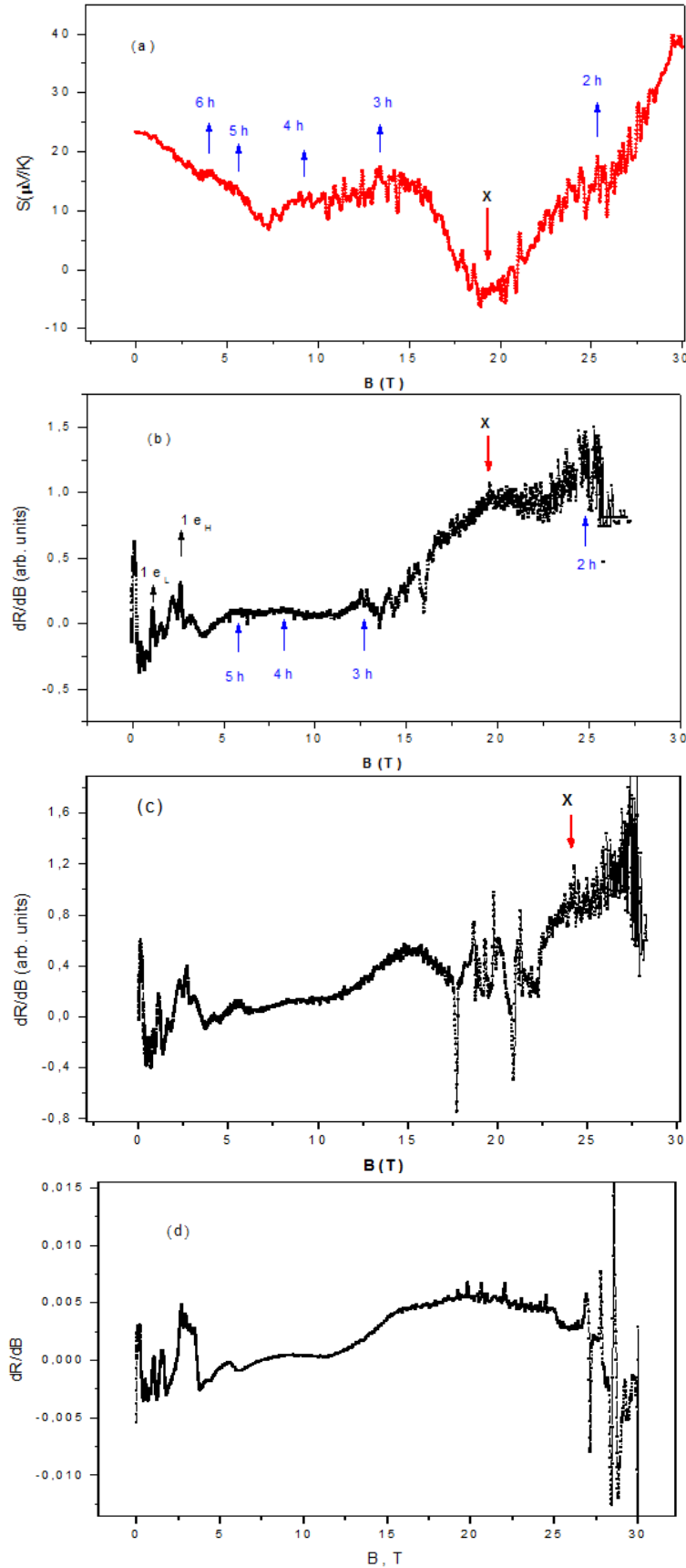


Fig. 3. (a) Seebeck coefficient as a function of magnetic field for Bi wire with $d = 400$ nm in a non-deformed state at $T = 4.2$ K. Red arrow indicates the position of the unidentified peak X; peaks of quantum oscillations from holes are indexed as $2_h, -5_h$.

(b) Derivative dependence dR/dB as a function of B for the MR in curve 1 in Fig. 3 for Bi wire in a non-deformed state. The positions of the QL of electrons coincide with the first peak $1e_H$ and $1e_L$ of the quantum oscillations from heavy and light electrons respectively.

(c) Derivative dependence dR/dB as a function of B for the MR in curve 2 in Fig. 3 for Bi wire at strain values $\varepsilon = 0.4\%$.

(d) Derivative dependence dR/dB as a function of B for the MR in curve 2 in Fig. 3 for Bi wire at strain values $\varepsilon = 1.0\%$.

Moreover, the prediction of the occurrence of an additional peak in the Nernst signal where the magnetic field is close to the bisectrix direction is an intriguing challenge for measurements in this configuration. Note that, on the MR and Seebeck dependences in a high field, we really observed double-splitting peaks attributed to the crossing of the Fermi level by the $j = 2$ and $j = 3$ Landau levels of holes at ~ 25.5 and ~ 14 T, respectively, i.e., close to the positions indicated in Fig. 5 in [13]. In addition to these peaks, an unidentified peak (denoted by X) was observed in a field of 19.5 T.

Further, a twinning scenario was suggested [6] where the origin of anomalous high-field peaks is attributed to the crossing of the Fermi energy level by the LLs of holes from a secondary twined crystal. Apparently, we could also assume the similar nature of unknown peak X, as we cannot exclude the possibilities of the presence of defects or twins in our Bi wires. However, there are several reasons for opposing this supposition: (i) assuming that the peak X is due to the crossing of the Fermi energy level by the $j = 2$ LLs of holes from a secondary twined crystal, one should expect the appearance of other holes peaks from a secondary twined crystal, however, in the experiments we did not observe any additional peaks, modulations, or beats in the visible period of the oscillations from holes; (ii) unidentified peak X is present at $B \approx 19$ T on MR and MTEP dependences for the set of wires with diameters of 0.3–0.6 and 1.1–1.3 μm . It is inconceivable that the wires obtained under the different technological conditions (diameter is given by the different temperatures and drawing speeds) may have the same twinning structure. Furthermore, the peak at 19 T persists in the Bi wires after the thermal annealing; (iii) the last contradiction is shared with the open question left in the conclusions of [6]: 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 a spontaneous symmetry breaking observed in the magnetostriction measurements where authors have failed to detect traces of secondary twined crystal. Thus, the basic contribution to the signal in magnetic field comes from the primary crystal.

In spite of above mentioned reasons, we cannot completely rule out a twinning scenario. We found additional peaks (supposed of holes from twins) in a magnetic field of 16–19 T at the tilted angle of 70° with the trigonal axis (that is the orientation of the Bi wires) in the figure of plotted Landau spectrum in the trigonal-bisectrix plane [6]. Accidentally or not, the position of our unidentified peak X coincide with the indicated magnetic field interval.

Another interpretation of the unusual Nernst peaks 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. 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 oriented along the trigonal axis where the LLL of electrons 0^- is filled, while the next LLL 0^+ 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 guides the discussion of our results in this context.

In the measurements, it was observed that the positions of the wiggles in a magnetic field and peak X following them exhibit the same tendency under strain; this fact suggests that they may have the same origin and can apparently be regarded as components of one complex anomaly. It is evident from Figs. 2 and 3 that the applied strain leads to a shift of the MR wiggles to higher magnetic fields simultaneously with an increase in the extreme cross sections of the

heavy electron ellipsoids. The movement of B_{QL} of the heavy electrons under strain is indicated by arrows in Fig. 2.

Might this anomaly be attributed to heavy electron ellipsoids?

It has already been noted [11, 30] that anomalous features associated with the electrons above the QL may arise in transport coefficients in a high magnetic field taking into account the electron–phonon effect, which can lead to a redistribution of the carriers between the pockets. We also may expect manifestation of this effect in Bi wires. In the case where the magnetic field is oriented along the bisectrix axis, the electron–phonon coupling can lead to a redistribution of heavy electrons between two equivalent ellipsoids B and C placed symmetrically relative to the direction of the magnetic field. This reasoning corresponds to the assumption [11] of the first-order phase transition due to the electron–phonon interaction and, generally speaking, could explain the presence of an additional peak at 19.5 T.

As concerns the wiggles, their presence at ~ 15 T on MR and MTEP dependences of non-deformed Bi wires for a long time was ignored supposing to be due to the mechanical vibrations of the cooling installation. In the previous paper [28] we acknowledged the unknown nature of the observed wiggles in the thermopower around 15 T. Further measurements of MR under strain revealed a dependence of the field position of the wiggles upon the modification of the energy spectrum during deformation. The profile of MR and MTEP dependences with anomalous features were reproduced before the strain and after the removal of stretching load.

We have attempted to justify the position of the anomalies at 15 T in terms of the model of two interacting LLLs proposed by Vecchi et al. [20] and developed it for the explanation of the anomalies in the magnetoreflexion line shape of bulk Bi, where it was found that two $j = 0$ levels of the conduction and valence bands approach each other and reach a point of minimum separation at about $B_{min} \approx 15$ T for a magnetic field applied parallel to the bisector axis (j is the quantum number of the LL). As has already been pointed out [21], the correlation effect, which is more pronounced in this interband coupling regime, enhances interactions between electrons from the LLL and the second LL and affects the electron–phonon coupling process, and these phenomena taken together may lead to an instability in the system that has an effect on the transport properties. The observed oscillating instabilities (wiggles) at $B \approx 15$ T can be attributed to the superimposition of two effects: electron–phonon coupling and enhanced electron interactions.

The electron–phonon effect and redistribution of heavy electrons results in an increase in the degeneracy of two equivalent ellipsoids B and C and the formation of Landau sublevels. In particular, the splitting of each electron level into few sublevels was predicted by theoretical calculations for a magnetic field oriented in the bisector–trigonal plane [20]. The calculated angular dependences of the magnetic field at which the electron LLs cross the Fermi energy level indicate a possible crossing of the Fermi level by the 0_e^+ Landau sublevel of heavy electrons in a magnetic field close to 20 T. The above examined ideas about the influence of the electron–phonon effect, redistribution of heavy electrons and splitting of the LLL electron level into a few sublevels do not contradict each other and allow for the understanding of an anomalous high-field peak in the frame of the one-particle picture.

Thus, the unknown peak X with a positive sign of the jump in the MR and with a negative sign in the MTEP dependences (Figs. 3a, 3b) in a magnetic field of 19.5 T can be identified with the crossing of the Fermi energy level by the one of the spin-polarized lowest Landau sublevels of heavy electrons that should be shifted to a high magnetic field with an increase in their QL under an applied strain (Figs. 3b–3d). In this context, we may speculate on the attribution of

unusual wiggles and the unidentified peak X in the MR and MTEP dependences to the complex structure of the LLLs of heavy electron pockets in a high magnetic field.

In our explanations, we have not discussed the assumption of the effect of the surface states on the transport in bismuth since we fully share the Comment on ‘Signatures of Surface States in Bismuth at High Magnetic Fields’ [16]. As concerns Bi wires, a manifestation of the surface states may be possible in thin nanowires with $d < 100$ nm. Our Bi wires with $d > 200$ nm exhibit bulk-like properties.

Finally, the magnetic field position of peak X is reproduced for wires with $d = 0.2\text{--}2.0$ μm without showing a dependence on the limiting size indicating their bulk origin. Moreover, the magnitude of the unidentified peak X is larger for the more structurally perfect wires of larger diameters $d = 1.0\text{--}2.0$ μm , where phonon drag effect is dominant in the thermopower. Further, the MTEP peak at 19.5 T persists up to a temperature of 10 K, where quantum oscillations from holes are smeared. Detailed results of investigations of MTEP in temperature ranges of 4.2 – 20 K where the phonon drag effect is dominant may be the subject of another paper.

3. Conclusions

Measurements of the longitudinal magnetoresistance in a pulsed magnetic field of up to 35 T with the orientation along the bisector axis have revealed some anomalies in a magnetic field above the QL of the electrons: a sharp peak of MR at 33 T and some oscillating instabilities in a magnetic field below 20 T.

Investigation of MR under uniaxial strain has revealed that the sharp peak of the MR is reproduced in lower magnetic fields at 28 T according to a decrease in the light electron concentration under strain. The Lifshitz ETT was recorded at a strain of 1.1% in the result of the vanishing of the light electron ellipsoid. Since the MR peak detected in the strained wire fades after the Lifshitz ETT, we suppose that the MR peaks at 33 and 28 T have the same origin, which is attributed to the crossing of the Fermi level by the LLL of light electrons. The present conclusions are consistent with the previous assumption [15] based on the model of Vecchi et al. [14] which implies a “camel-back” structure in the k_H dispersion of the LLL for light electrons. Thus, a correlation between the exit of the LLL of light electrons and the Lifshitz transition has been found. The result is that the critical magnetic field of the ETT has decreased; thereby, the magnetic field range of occurrence of magnetic-field-induced instabilities associated with the LLLs of electrons has been extended.

The investigation of MR and Seebeck coefficient under the simultaneous action of a strain and a magnetic field has revealed a modification of the electronic structure where the QL for light and heavy electrons changes in different ways: QL_L of the light electrons decreases with a decrease in their concentration owing to the transfer to two equivalent ellipsoids of heavy electrons, while QL_H of the heavy electrons moves to a high magnetic field.

The observed correlation between the shift of QL_H of heavy electrons to a high magnetic field and the position of the MR anomalies (wiggles followed by an unidentified peak at 19.5 T) suggests that these effects can be attributed to the crossing of the Fermi level by the one of lowest Landau sublevels of heavy electrons that should be shifted to a high magnetic field with an increase in their QL. In this context, we may speculate on the attribution of the wiggles (oscillations) and the unidentified peak in the MR and MTEP dependences to the complex structure of the LLLs of heavy electron pockets in a higher field.

It should also be noted that a decrease in the resistance in higher fields with the apparent metallization of bismuth indicates possible changes in the mechanism of carrier scattering [2, 21]

associated also with the Lifshitz transition and with the substructure of the LLL of electrons.

The observed anomalies in the MR in a high magnetic field have been explained in terms of well-known models of the energy spectrum for bulk Bi additionally considering the performed theoretical calculations [5, 10, 11, 13, 20, 21]. Note that it cannot be ruled out that the observed anomalies may have a more exotic origin, which requires accurate theoretical calculations in the future. Some refinements on the contribution of electrons or holes to the anomalies in magnetotransport will be obtained through future experimental measurements of the Seebeck effect in a high magnetic field of up to 35 T.

Acknowledgments. This work was supported by a Polish-Moldovan bilateral project (PAN-2014-2016). The author acknowledges the support from EuroMagNET under the EU contract for access to the High Field Magnet Laboratory and Institute for Molecules and Materials, Radboud University in Nijmegen.

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