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Regular Article

Near-surface thermal generation of longitudinal bulk acoustic waves in organic conductors

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Abstract. The linear thermal generation of near-surface longitudinal bulk acoustic waves (NSLBAWs) in organic conductors with layered structure is considered. These are waves that are generated and propagate at a distance of order or less than the thermal source attenuation length, *i.e.*, are confined to the thermal skin layer of the conductor. The Green's functions approach is applied to obtain the integral form for the solutions of the thermal conduction equation and wave equation. Analytical expressions for the temperature distribution and the wave amplitude are obtained in case when a current is applied along the least conducting direction of the quasi-two-dimensional organic conductor $\beta-(\mathrm{BEDT}-\mathrm{TTF})_2\mathrm{IBr}_2$ as a thermal source. The behavior of both thermal and acoustic field is investigated near the conductor's surface. In addition, the angular and magnetic field dependencies of the NSLBAWs amplitude are obtained and analyzed in order to emphasize the specific features of these waves. Furthermore, a comparison of the properties of both NSLBAWs and the longitudinal bulk acoustic waves that are generated and attenuate in the depth of the conductor, *i.e.*, deep longitudinal bulk acoustic waves (DLBAWs) reveals some similarities and important differences in the process of thermal generation of the waves. We discuss the possible application of the thermal generation of NSLBAWs in organic conductors and why these waves are more preferable than the DLBAWs for studying some of the properties and/or states in layered organic conductors as well as for determining the parameters that shape the Fermi surface that cannot be obtained through the DLBAWs or transport measurements.

1 Introduction

In conducting media, acoustic waves can be generated trough different mechanisms in the linear or nonlinear regime depending on the source and on the properties of the material. In the presence of an external magnetic field the inductive and thermoelectric mechanisms are the most important [1]. The former is due to the Lorentz force acting on the conduction electrons and the latter is associated with the nonuniform temperature oscillations induced by a thermal source. The properties of the material will determine the type of acoustic wave that will be generated and the mechanism of control. The investigation of thermoacoustic generation in different materials, especially in those with strong anisotropy, might give information about the structure, properties and transport since the production of acoustic waves through this mechanism is related to both the thermal and elastic properties of the material.

From the variety of acoustic waves that can propagate in conducting media, the longitudinal bulk acoustic waves (LBAWs) that are thermally generated near the conductor's surface might give useful insights on how the wave and thermal properties of the conductors change in the proximity to the surface and thermal source, *i.e.*, in the thermal skin layer where they are much more influenced by both the surface and source. In this respect, the investigation of the LBAWs behavior in the vicinity of the surface of the material is important, additionally to the investigation of the surface acoustic waves (SAWs), in obtaining more information not only about the wave and thermal properties of conductors but also the parameters that determine their Fermi surface and energy spectrum.

In a broader context, the knowledge of LBAWs thermal generation and propagation in the vicinity of the surface in complex systems exhibiting anisotropic properties, and such are layered organic materials, can help understand the

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complex thermal transport in these compounds, which is very significant if these materials are to be used for a design of electroacoustic devices.

Analyses of bulk acoustic waves in layered organic structures that are thermally generated and propagate in the depth of the conductor (away from the surface and hence from the thermal source) have been conducted and reported in the literature [2–5], but so far there have been no studies on the behavior of bulk acoustic waves that are thermally generated near the conductor's surface. Layered conductors of organic origin are attractive for experimenters to a considerable extent due to their peculiar behavior in strong magnetic fields and a number of phase transitions under comparatively low pressures [6]. Their electrical conductivity along layers is by several orders of magnitude higher than electrical conductivity along the normal to the layers, and the critical magnetic field at which superconductivity is violated considerably depends on its orientation relative to the layers. Organic conductors are interesting for applications owing to the diversity of high-frequency and magnetoacoustic phenomena typical of conductors with low-dimensional electron energy spectra. High-frequency parameters of layered conductors are very informative, and their analysis will make it possible to determine fine details of the electron energy spectrum and relaxation properties of charge carriers.

In this paper we present a comprehensive study of the thermal generation and propagation of the NSLBAWs in quasi-two-dimensional organic conductors. Information on their properties and insights on the charge carriers involved in the generation are obtained by analyzing the thermal and acoustic field as well as through magnetic field and angular dependence. We also make a comparison between NSLBAWs and DLBAWs in order to emphasize the similarities and differences in the process of their thermal generation. Surprisingly, we find that there are more differences than similarities in their behavior that could significantly contribute in understanding the wave processes in organic conductors in general.

2 Formulation of the NSLBAWs thermal generation problem: The Green's functions method

We apply the Green's functions method to solve both the thermal conduction and acoustic wave equation for a given harmonic thermal source with a frequency ω at the conductor's surface in order to calculate and analyze the temperature and acoustic field distribution for the NSLBAWs. This approach is an elegant one in a way that it allows the solutions for the temperature distribution and wave amplitude to be represent in an integral form which can be further used for both numerical and analytic calculations.

The NSLBAWs are thermally generated under the conditions of normal skin effect, when the electron mean-free path length l is much smaller than the thermal field length δ_T of the conductor, $l \ll \delta_T$. We shall consider a mechanically stress free boundary for the conduction electrons involved in the generation to scatter elastically from the surface. These waves can be launched only through linear thermal generation when the coupling between the thermal and acoustic oscillations is weak. This is necessary for the detection of thermally generated NSLBAWs as they have smaller amplitude compared to that of DLBAWs. In addition, the thermal generation is possible when the quasi-static condition $\omega\tau \ll 1$, τ is the relaxation time of the conduction electrons, is fulfilled. For most of the organic conductors, the relaxation time is very small, of order $\tau \sim 10^{-11}$–10^{-12} s, allowing the generation of bulk acoustic waves to occur and be observed even for high frequencies of the thermal source up to $\omega = 10^{11}$ Hz.

2.1 Thermal conduction equation for the NSLBAWs generation-integral and analytical solutions

We shall first determine the temperature distribution Θ within the conductor by solving the thermal conduction equation

$$C\frac{\partial \Theta}{\partial t} + \operatorname{div}\mathbf{q} = 0, \tag{1}$$

which involves the thermal flux arising from the thermal source and thermoelectric effect. For this we need the expression for the thermal flux resulting from the external perturbation in the form of an electric field $\mathbf{E}$ and temperature Θ,

$$q_i = T\alpha_{ij}E_j - \kappa_{ij}\frac{\partial \Theta}{\partial x_j}\,. \tag{2}$$

Here T is the equilibrium temperature of the crystal, C is the volumetric heat capacity of the conductor, α_{ij} is the thermoelectric coefficient tensor, κ_{ij} is the interlayer thermal conductivity tensor.

In organic conductors, the z- and x-axis correspond to the least and most conductive direction, respectively. Therefore, most of their properties are studied for geometries that involve these directions. In this regard, here we consider a NSLBAWs generation caused by a harmonic thermal source for example, by heating the conductor locally with applying a current $\mathbf{j} = (j_x, 0, 0)$ of frequency $\omega = 10^9$ Hz along the z-axis of the conductor as shown in fig. 1.

The source induces nonuniform temperature oscillations of the same frequency which in turn generate longitudinal NSLBAWs (along the z-axis) in the conductor with the same frequency. Using the Maxwell's equations for a magnetic

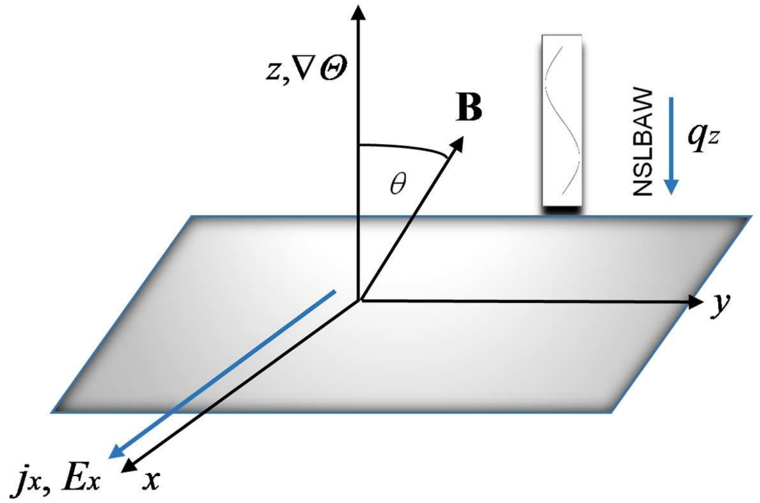

Fig. 1. Geometry for the NSLBAWs thermal generation in organic conductors. The corresponding quantities relevant for the problem described in the text are indicated for reference.

field orientation in the yz plane, $\mathbf{B} = (0, B\sin\theta, B\cos\theta)$, and an electric field $\mathbf{E} = (E_x, 0, 0)$ (fig. 1) we present the current, not altered by the thermoelectric forces, in the following form: $j_x(z) = j_x(0)e^{ik_E z}$, where $j_x(0) = -i\frac{k_E}{\mu_0}B_y(0) = -i\frac{k_E}{\mu_0}B(0)\sin\theta$, μ_0 is the magnetic permeability of vacuum and $B(0)$ is the magnetic field strength at the conductor's surface. When wave processes are considered in the proximity to the surface taking into account the magnetic field at the surface, $B(0)$, is important because of its influence on the conduction electrons that are involved in the process of generation. This field has a negligible influence on the DLBAWs but can significantly alter the amplitude of the NSLBAWs and therefore must be included in the corresponding differential equations that describe the problem of NSLBAWs thermal generation.

This allows us to write down the accompanying electric field as $E_x(z) = \frac{\omega B(0)\sin\theta}{k_E}e^{ik_E z}$ and the thermal flux within the conductor takes the following form:

$$q_z = \frac{T\alpha_{zx}\omega B(0)\sin\theta}{k_E}e^{ik_E z} - \kappa_{zz}\frac{\partial\Theta}{\partial z}\,. \tag{3}$$

The thermal conduction equation is then written as

$$\frac{\partial^2\Theta}{\partial z^2} + k_T^2\Theta = Q_0 e^{ik_E z}\,, \quad Q_0 = i\frac{T\alpha_{zx}}{\kappa_{zz}}\omega B(0)\sin\theta. \tag{4}$$

Here α_{zx} and κ_{zz} are the thermoelectric coefficient and interlayer thermal conductivity component, respectively. The electromagnetic wave number and skin depth are defined as

$$k_E = \frac{1+i}{\delta_E}, \quad \delta_E = \sqrt{\frac{2}{\omega\mu_0\sigma_{xx}}}\,, \tag{5}$$

and

$$k_T = \frac{1+i}{\delta_T}\,, \quad \delta_T = \sqrt{\frac{2\kappa_{zz}}{\omega C}} \tag{6}$$

are the thermal wave number and skin depth. In eq. (5), σ_{xx} is the in-plane electrical conductivity.

In the following we will first obtain the relations for the temperature distribution within the conductor for isothermal and adiabatic boundary conditions, $\Theta_I(0) = 0$ and $\Theta'_A(0) = 0$, respectively. In addition, it is natural to assume that in the depth of the conductor the temperature Θ is equal to the equilibrium temperature T of the conductor, so that $\Theta_{I,A} = 0$ when $z \to \infty$.

The general solution of eq. (4) expressed in terms of Green's functions is given as

$$\Theta(z) = Q_0\left(\int_0^z G_2(z,\xi)e^{ik_E z}|_{z=\xi}\mathrm{d}\xi + \int_z^\infty G_1(z,\xi)e^{ik_E z}|_{z=\xi}\mathrm{d}\xi\right), \tag{7}$$

where $G_1(z,\xi)$ and $G_2(z,\xi)$ are the corresponding Green's functions, which are obtained by solving the homogeneous differential equation

$$\frac{\partial^2 G(z,\xi)}{\partial z^2} + k_T^2 G(z,\xi) = 0. \tag{8}$$

When DLBAWs are considered in an organic conductor the process of generation is confined to a distance much larger than the thermal source attenuation length ($z \gg \delta_T$) and in that case only the first term in eq. (7) with the upper limit replaced with ∞ is important for calculation of both the temperature distribution and wave amplitude [5]. On the other hand, for wave processes that take place in the vicinity of the surface, when waves are generated at a distance of order or less than the thermal source attenuation length ($z \lesssim \delta_T$) such as NSLBAWs both terms in eq. (7) must be taken into account when obtaining the relations for the temperature distribution within the conductor and wave amplitude.

2.1.1 Green's functions for the temperature distribution at isothermal boundary

Using the homogeneous boundary conditions at $z = 0$ and $z = \infty$ for the Green's function and the two additional conditions that involve the continuity and jump at $z = \xi$, the corresponding Green's functions are obtain as follows:

$$\begin{aligned} G_1(z,\xi) &= -\frac{1}{k_T}\sin(k_T z)e^{ik_T\xi}, \quad z < \xi \\ G_2(z,\xi) &= -\frac{1}{k_T}\sin(k_T \xi)e^{ik_T z}, \quad z > \xi. \end{aligned} \tag{9}$$

Substituting the obtained Green's functions into eq. (7) the integral form of the solution for the temperature distribution is written as

$$\Theta_I(z) = -\frac{Q_0}{k_T}\left(e^{ik_T z}\int_0^z \sin(k_T\xi)e^{ik_E\xi}\mathrm{d}\xi + \sin(k_T z)\int_z^\infty e^{i(k_T+k_E)\xi}\mathrm{d}\xi\right), \tag{10}$$

which yields the following analytical expression for the temperature distribution in case of an isothermal boundary condition:

$$\Theta_I(z) = Q_0\frac{e^{ik_E z} - e^{ik_T z}}{k_T^2 - k_E^2}\,. \tag{11}$$

2.1.2 Green's functions for the temperature distribution at adiabatic boundary

Again, applying the Green's functions method and the accompanying boundary conditions we obtain the following Green's functions:

$$\begin{aligned} G_1(z,\xi) &= \frac{1}{ik_T}\cos(k_T z)e^{ik_T\xi}, \quad z < \xi, \\ G_2(z,\xi) &= \frac{1}{ik_T}\cos(k_T \xi)e^{ik_T z}, \quad , z > \xi, \end{aligned} \tag{12}$$

which, substituted in eq. (7), yields the following integral form for the temperature distribution

$$\Theta_A(z) = -i\frac{Q_0}{k_T}\left(e^{ik_T z}\int_0^z \cos(k_T\xi)e^{ik_E\xi}\mathrm{d}\xi + \cos(k_T z)\int_z^\infty e^{i(k_T+k_E)\xi}\mathrm{d}\xi\right). \tag{13}$$

For the given thermal source we obtain the following temperature distribution in case of an adiabatic thermal condition:

$$\Theta_A(z) = Q_0\frac{e^{ik_E z}k_T - e^{ik_T z}k_E}{k_T(k_T^2 - k_E^2)}\,. \tag{14}$$

2.2 Integral and analytical solutions for the NSLBAWs amplitude

The amplitude of thermally generated waves is obtained by solving the acoustic wave equation. Since the harmonic thermal source and hence the induced temperature oscillations are along the less conducting axis, the z-axis of the conductor, the generated waves are longitudinal. In that case the acoustic wave equation is written in the following form:

$$\frac{\partial^2 U_{\mathrm{NSLBAW}}(z)}{\partial z^2} + q^2 U_{\mathrm{NSLBAW}}(z) = \beta\frac{\mathrm{d}\Theta}{\mathrm{d}z}\,, \tag{15}$$

where $q = \omega/s$ is the wave vector, s is the wave velocity, β is the volumetric expansion coefficient. The solution of the acoustic wave equation in terms of Green's functions is written as

$$U^{I,A}_{\mathrm{NSLBAW}}(z) = \beta\left(\int_0^z G_2(z,\xi)\frac{\mathrm{d}\Theta_{I,A}}{\mathrm{d}z}\bigg|_{z=\xi}\mathrm{d}\xi + \int_z^\infty G_1(z,\xi)\frac{\mathrm{d}\Theta_{I,A}}{\mathrm{d}z}\bigg|_{z=\xi}\mathrm{d}\xi\right). \tag{16}$$

We take into account that the wave amplitude satisfies the mechanical stress free boundary condition $(U^{I,A}_{\mathrm{NSLBAW}}(0))' = 0$. Applying the Green's functions approach the following integral solutions are obtained for isothermal and adiabatic condition, respectively:

$$U^{I,A}_{\mathrm{NSLBAW}}(z) = -\beta\left(ie^{iqz}\int_0^z \sin(q\xi)\Theta_{I,A}(\xi)\mathrm{d}\xi + \cos(qz)\int_z^\infty e^{iq\xi}\Theta_{I,A}(\xi)\mathrm{d}\xi\right). \tag{17}$$

The corresponding expression for the wave amplitude in a case of a free isothermal boundary, obtained by substituting eq. (11) into eq. (17), is written as

$$U^{I}_{\mathrm{NSLBAW}}(z) = i\beta Q_0\frac{qk_T(e^{iqz}k_T - e^{ik_Tz}q) + k_E^2(e^{ik_Tz}k_T - e^{iqz}q) + e^{ik_Ez}k_E(q^2-k_T^2)}{(q^2-k_E^2)(q^2-k_T^2)(k_T^2-k_E^2)}. \tag{18}$$

For a free adiabatic boundary the wave amplitude, obtained by substituting eq. (14) into eq. (17), is written as

$$U^{A}_{\mathrm{NSLBAW}}(z) = i\beta Q_0\frac{k_E^3(e^{ik_Tz}k_T - e^{iqz}q) + e^{iqz}qk_T(k_T^2-q^2) + k_E(e^{iqz}q^3 + q^2k_T(e^{ik_Ez}-e^{ik_Tz}) - e^{ik_Ez}k_T^3)}{k_T(q^2-k_E^2)(q^2-k_T^2)(k_T^2-k_E^2)}. \tag{19}$$

The complex amplitude of the thermally generated NSLBAWs is a function of the frequency of the thermal source ω, magnetic field strength B and the angle between the normal to the layers plane and the magnetic field θ. In addition, the transport coefficients, such as electrical conductivity, thermoelectric coefficient and thermal conductivity, play a significant role in determining the behavior of thermally generated waves. Therefore, the calculation of these coefficients is very important in order to study the wave properties in organic conductors.

When the quantum oscillations of transport coefficients are not considered, their magnetic field and angular dependence can be determined on the basis of the Boltzmann transport equation [7] by taking into account the structure of electronic energy spectrum. The components of the electrical conductivity tensor in the frame of Boltzmann transport theory can be approximately evaluated as follows:

$$\sigma_{ij} = \frac{2e^3B}{(2\pi\hbar)^3}\int\frac{\partial f_0}{\partial\varepsilon}\mathrm{d}\varepsilon\int\mathrm{d}p_B\int_0^{T_B}\mathrm{d}t v_i(t)\int_{-\infty}^t \mathrm{d}t' v_j(t')e^{\frac{t'-t}{\tau}}. \tag{20}$$

Here $p_B = p_y\sin\theta + p_z\cos\theta = \text{const.}$ is the momentum component along the magnetic field $\mathbf{B}$. The topologically simplest model of a Fermi surface for quasi-two-dimensional conductors, a slightly warped cylinder, is in good agreement with the results of experimental studies of the magnetoresistance and the de Haas-van Alphen effects in many organic layered conductors [6]. We consider NSLBAWs generation in a layered organic conductor, whose Fermi surface is a slightly warped cylinder with an arbitrary shape of the transverse cross-section. The electron energy spectrum of such system is expressed as

$$\varepsilon(\mathbf{p}) = \frac{p_x^2+p_y^2}{2m^*} - 2t_c\cos\left(\frac{cp_z}{\hbar}\right). \tag{21}$$

Here, the x- and z-axes are associated with the most and the least conducting directions, c is the interlayer lattice constants, t_c is the interlayer transfer integral, $\hbar$ is Planck's constant and m^* is the charge carrier effective mass. The conductivity tensor component σ_{zz}, in the case of the charge carrier dispersion relation (21), has the form

$$\sigma_{zz} = \sigma_0\left(J_0^2\left(\frac{cp_F}{\hbar}\tan\theta\right) + \frac{2\gamma^2J_1^2(\frac{cp_F}{\hbar}\tan\theta)}{\gamma^2+B^2\cos^2\theta}\right). \tag{22}$$

Here σ_0 is the electrical conductivity in the plane of the layers in the absence of a magnetic field, p_F is the Fermi momentum, $\gamma = m^*/e\tau$ and J_k is the k-th–order Bessel function.

Using eq. (20) and the equations of motion for the conduction electrons in a magnetic field $\mathbf{B} = (0, B\sin\theta, B\cos\theta)$, the rest of the electrical conductivity components are obtained as follows:

$$\sigma_{xx} = \frac{\gamma^2}{\gamma^2+B^2\cos^2\theta}(\sigma_0 - \sigma_{zz}\tan^2\theta), \tag{23}$$

$$\sigma_{zx} = -\frac{\gamma B\cos\theta}{\gamma^2+B^2\cos^2\theta}\sigma_{zz}\tan\theta. \tag{24}$$

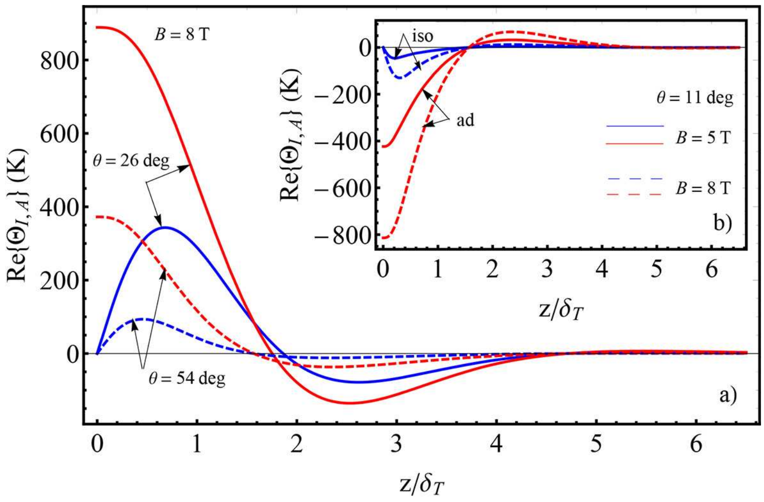

Fig. 2. The dependence of the rel part of the temperature distribution near the surface in the organic conductor $\beta-(\mathrm{BEDT}-\mathrm{TTF})_2\mathrm{IBr}_2$ on the parameter z/δ_T for $T = 20\,\mathrm{K}$ and $B(0) = 3\,\mathrm{T}$ at (a) $B = 8\,\mathrm{T}$ and $\theta = 26^\circ$, $\theta = 54^\circ$; (b) $\theta = 11^\circ$ and $B = 5\,\mathrm{T}$, $B = 8\,\mathrm{T}$ for isothermal (blue curves) and adiabatic (red curves) condition.

The thermoelectric transport coefficients are usually obtained by means of electrical conductivity components using the Mott formula, $\alpha_{ij} = \frac{\pi^2 k_B^2 T}{3e}\frac{\partial \sigma_{ij}}{\partial \varepsilon}|_{\varepsilon=\mu}$. Thus, the thermoelectric coefficient component α_{zx} is calculated as

$$\alpha_{zx} = \frac{2\pi^2 k_B^2 T\sigma_0}{3e\mu}\frac{\gamma B\cos\theta}{(\gamma^2 + B^2\cos^2\theta)^2} J_0(x)J_1(x)\tan\theta\left(\gamma^2 J_2(x)/J_0(x) - B^2\cos^2\theta\right), \tag{25}$$

where k_B is the Boltzmann constant, μ is the chemical potential of the electron system and $x = \frac{cp_F}{\hbar}\tan\theta$.

The Wiedemann-Franz law for the thermal conductivity, $\kappa_{ij} = \frac{\pi^2 k_B^2 T}{3e^2}\sigma_{ij}$, is used to determine the thermal conductivity component κ_{zz} as

$$\kappa_{zz} = \frac{\pi^2 k_B^2 T\sigma_0}{3e^2}\left(J_0^2(x) + \frac{2\gamma^2 J_1^2(x)}{\gamma^2 + B^2\cos^2\theta}\right). \tag{26}$$

3 Results and discussion

In this section we first analyze how the thermal field distribution in case of NSLBAWs generation in the model organic conductor $\beta-(\mathrm{BEDT}-\mathrm{TTF})_2\mathrm{IBr}_2$ changes with distance from the surface. This is important in order to obtain information on how the corresponding acoustic wave field changes with distance as well as on the magnetic field and angular dependence of the NSLBAWs amplitude. The figures obtained here are for $T = 20\,\mathrm{K}$, $\gamma = 2.365$ and $cp_F/\hbar = 5$ [6]. For obtaining the corresponding dependencies we chose a lower value for the magnetic field at the surface of the conductor, $B(0) = 3\,\mathrm{T}$, in order to avoid the additional anisotropy introduced by field at the beginning of the process of NSLBAWs generation.

3.1 Thermal field distribution for the NSLBAWs generation

Figure 2 shows the dependence of the real part of induced isothermal and adiabatic temperature distribution in the organic conductor $\beta-(\mathrm{BEDT}-\mathrm{TTF})_2\mathrm{IBr}_2$ on the parameter z/δ_T at different magnetic fields B and orientations θ. The main panel of fig. 2 corresponds to a constant magnetic field and different angles with respect to the layers while the inset of fig. 2 is for a constant angle and different magnetic fields.

We first note that the temperature distribution is zero at conductor's surface ($z = 0$) for the isothermal condition, $\Theta_I(0) = 0$, but there is non-vanishing temperature distribution at the adiabatic boundary, $\Theta_A(0) = Q_0/k_T(k_T + k_E)$. This is in agreement with the thermal boundary conditions according to which the heat flux exists only trough the isothermal boundary. It is evident that in organic conductors, the induced temperature oscillations are magnetic field and angle-dependent. As can be seen from fig. 2(a), the attenuation of the temperature oscillations at constant field and different angles of orientation occurs at $z \sim 4.8\,\delta_T$ while they are present up to $z \sim 4.4\,\delta_T$ in case when the angle is the same and the magnetic field strength is changed (fig. 2(b)). This corresponds to a distance of $z \sim 1.5$–$3.6\,\mathrm{mm}$

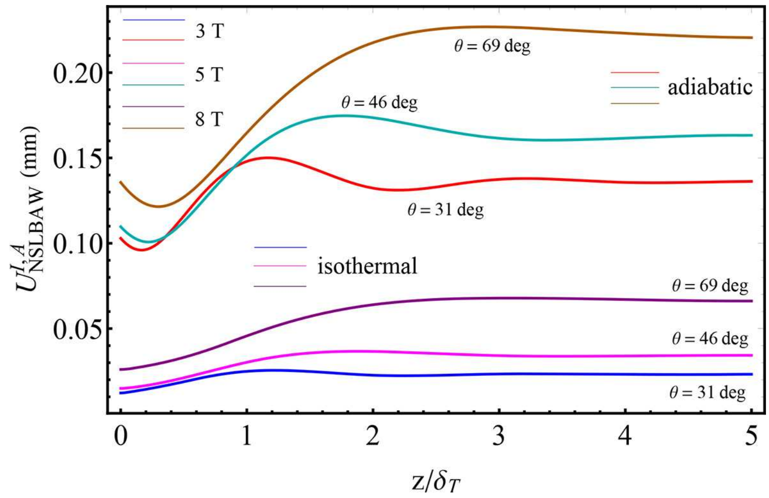

Fig. 3. The dependence of the NSLBAW amplitude in organic conductor $\beta-(\mathrm{BEDT}-\mathrm{TTF})_2\mathrm{IBr}_2$ on the parameter z/δ_T at $T = 20\,\mathrm{K}$ and $B(0) = 3\,\mathrm{T}$ for different magnetic field strength: $B = 3, 5$ and $8\,\mathrm{T}$ and angles from the normal to the layers: $\theta = 31^\circ, 46^\circ$ and 69°. The blue, magenta and purple curves are for the isothermal condition while the red, cyan and brown curves are for the adiabatic boundary.

from the conductor's surface and allows the value of the thermal skin depth δ_T to be determined. For the organic conductor $\beta-(\mathrm{BEDT}-\mathrm{TTF})_2\mathrm{IBr}_2$ we obtain that it is in the interval $\delta_T \sim 0.31$–$0.82\,\mathrm{mm}$ depending on the magnetic field strength and orientation. This value is in the interval $\delta_T \sim 0.32$–$1.2\,\mathrm{mm}$ previously obtained from the second harmonic wave magnetic field and angular dependence in this conductor [4]. Since the electromagnetic skin depth in $\beta-(\mathrm{BEDT}-\mathrm{TTF})_2\mathrm{IBr}_2$ is much smaller than the thermal skin depth, $\delta_E \sim 0.12\,\mathrm{mm}$ [8], this suggests that the wave generation, when occurring near the surface, is confined only to the thermal skin layer of the conductor and therefore it is mainly affected by the thermal and not electrodynamic characteristics of the conductor.

It is important to emphasize that the temperature distribution is larger for the adiabatic thermal condition. This is a consequence of the fixed boundary condition that makes the adiabatic boundary more preferable for the NSLBAWs thermal generation as in that case waves with larger amplitude are generated. Another issue to consider is the apparent slight shift of the maximum and minimum positions in the temperature distribution for both thermal boundaries with the magnetic field strength and its orientation. With increasing angle θ at constant field B the maximum and minimum are slightly shifted towards lower values of z/δ_T, whereas with increasing field at given angle their position is shifted to higher values of z/δ_T. This is associated with the quasi-two-dimensional character of the organic conductors. Namely, it is the reduced dimensionality of the organic conductor $\beta-(\mathrm{BEDT}-\mathrm{TTF})_2\mathrm{IBr}_2$ that leads to a shift of the positions of extremes in the magnetic field and angular dependencies of the corresponding transport coefficients that determine the temperature distribution. Since the NSLBAWs amplitude is determined by the same transport coefficients as the temperature distribution, this behavior is expected to be reflected in the NSLBAWs amplitude as well. This is discussed in detail below by studying the acoustic field distribution and the magnetic field and angular dependencies of the NSLBAWs amplitude.

3.2 Acoustic field distribution near the organic conductor's surface

Figure 3 shows the dependence of the NSLBAWs amplitude in the organic conductor $\beta-(\mathrm{BEDT}-\mathrm{TTF})_2\mathrm{IBr}_2$ on the parameter z/δ_T for both thermal conditions at different magnetic fields B and angles θ. It is obvious that the NSLBAWs amplitude is non-vanishing at $z = 0$ for both isothermal and adiabatic case in accordance with the corresponding boundary conditions for a stress free mechanical boundary. Also, for the organic conductor $\beta-(\mathrm{BEDT}-\mathrm{TTF})_2\mathrm{IBr}_2$, the adiabatic boundary is more preferable for the wave generation in agreement with the larger temperature distribution at this boundary. Furthermore, the amplitude of the thermally generated NSLBAWs has an oscillating character which is more pronounced at lower fields and smaller tilt angles from the normal to the layers.

As expected, the oscillating character of the wave amplitude is magnetic field and angle dependent and present up to distance of $z \sim 4.4$–$4.8\,\delta_T$ from the surface that corresponds to the temperature oscillations attenuation distance observed in fig. 2. Most strikingly, the wave amplitude is not decreasing drastically above these values of z/δ_T, as is the case for the SAWs amplitude, but it rather reaches a saturation. This means that as the generation of NSLBAWs is confined to the thermal skin layer their energy does not dissipate right after the generation but gradually penetrates partially into the depths of the conductor.

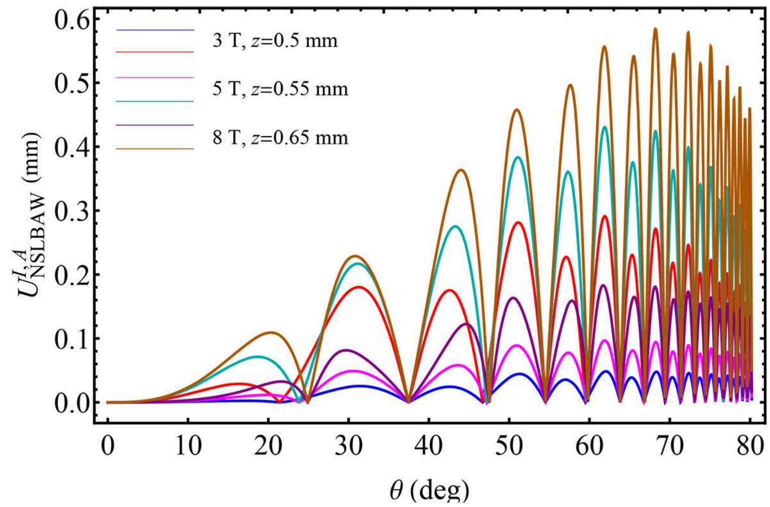

Fig. 4. Angular dependence of the NSLBAWs amplitude in the organic conductor $\beta-(\mathrm{BEDT}-\mathrm{TTF})_2\mathrm{IBr}_2$ at $T=20\,\mathrm{K}$, $B(0)=3\,\mathrm{T}$, $z=0.5, 0.55, 0.65\,\mathrm{mm}$ and several magnetic field strengths: $B=3, 5$ and $8\,\mathrm{T}$ from bottom to top. The blue, magenta and purple curves are for the isothermal condition while the red, cyan and brown curves are for the adiabatic condition.

The oscillating NSLBAW amplitude is associated not only with the harmonic thermal source but also with the averaged interlayer velocity of the conduction electrons $\bar{v}_z \simeq v_F J_0(\frac{cp_F}{\hbar}\tan\theta)$ (v_F is the Fermi velocity) that take part in the generation. Indeed, as the averaged interlayer velocity decreases with increasing angle this results in more pronounced oscillating behavior of the wave amplitude at smaller angles close to the normal to the layers. Otherwise, at larger angles the elliptical orbit along which the electrons travel (it is their trajectory in the plane perpendicular to the magnetic field presented in fig. 5 below) becomes more elongated and it takes longer time than the relaxation time τ for the electrons to make a full resolution along the orbit. This, in turn, results in less pronounced oscillating NSLBAWs amplitude at larger angles as seen from fig. 3.

It is evident that the NSLBAWs generation is most effective not at the conductor's surface (as in the case of SAWs [9]) but at certain distance z from the surface. At lower fields and smaller tilt angles the effectiveness of NSLBAWs generation is the largest at distance of order of the thermal skin depth, $z \sim \delta_T$, whereas with increasing field and tilt angle the effectiveness of the process is shifted towards the higher values of the parameter z/δ_T. Moreover, the peak in the NSLBAWs amplitude for both isothermal and adiabatic thermal condition occurs around the same value of z/δ_T for a given magnetic field strength and orientation.

The dependence of the NSLBAWs amplitude on the parameter z/δ_T shown in fig. 3 allows us to find the distance from the surface at which the wave generation is most effective in the organic conductor $\beta-(\mathrm{BEDT}-\mathrm{TTF})_2\mathrm{IBr}_2$. At low field and angles close to the normal to the layers, for example at $B=3\,\mathrm{T}$ and $\theta=31°$, the wave amplitude is the largest at $z=1.15\,\delta_T$. With increasing field and tilt angle, the wave generation is most effective at larger distance from the surface that significantly exceeds the thermal skin depth. Thus, at $B=5\,\mathrm{T}$ and $\theta=46°$, the wave amplitude is the largest at $z=1.8\,\delta_T$ while, at higher fields and angles close to the plane of the layers, such as for $B=8\,\mathrm{T}$ and $\theta=69°$, the peak in the wave amplitude occurs at $z=2.95\,\delta_T$. We suggest that it is the anisotropy in the transport coefficients introduced with increasing external magnetic field, in addition to highly anisotropic nature of organic conductors, that leads to a significant shift in the maximum efficiency of the thermal generation of waves in these conductors. The values of the parameter z/δ_T at which the peak in the wave amplitude is observed correspond to a distance of $z=0.5, 0.55$ and $0.65\,\mathrm{mm}$ from the conductor's surface, respectively. Taking into account the values obtained above for the thermal skin depth δ_T we find that the NSLBAWs generation is most effective at distance that is more than half the thermal skin depth but the process is confined to the thermal skin layer, *i.e.*, for $\delta_T/2 < z < \delta_T$.

3.3 Angular dependent NSLBAWs amplitude

Figure 4 shows the angular oscillations of the NSLBAWs amplitude at $T=20\,\mathrm{K}$ in $\beta-(\mathrm{BEDT}-\mathrm{TTF})_2\mathrm{IBr}_2$ for both thermal boundaries at different magnetic fields B and distance from the conductor's surface. The distance of $z=0.5, 0.55$ and $0.65\,\mathrm{mm}$ used for obtaining the angular dependencies corresponds to the one where the peak in the NSLBAWs amplitude dependence on z/δ_T occurs in fig. 3 for a given field.

The angular dependence of the NSLBAWs amplitude is characterized with an existence of strong oscillations whose amplitude becomes larger with increasing field. In organic conductors, the conduction electrons that are responsible for the wave generation perform periodic motion on closed orbits. Such a periodic motion of the electrons that emanates from the complex quasi-two-dimensional electron energy structure and corrugated Fermi surface results in an appearance of angular oscillations in the transport coefficients and hence, in the acoustic waves amplitude.

Since we are considering NSLBAWs whose amplitude depends essentially on the interlayer velocity averaged over the period of the electron motion on the closed orbit $\bar{v}_z$ it is reasonable to analyze the observed angular oscillations of the wave amplitude through how $\bar{v}_z$ changes when electrons transverse different parts of the closed orbits. With tilting the field from the direction normal to the layers, the interlayer velocity $v_z = \frac{\mathrm{d}\epsilon}{\mathrm{d}p_z} = \frac{2t_c c}{\hbar}\sin(cp_z(t)/\hbar)$ oscillates more rapidly and thus the average over the cyclotron period interlayer velocity, $\bar{v}_z \simeq v_F J_0(\frac{cp_F}{\hbar}\tan\theta)$, decreases with increasing angle but the drift velocity of conduction electrons along the x-axis, $\bar{v}_x \simeq v_F\sqrt{1-J_0^2(\frac{cp_F}{\hbar}\tan\theta)(1+\tan^2\theta)}$, is rather large at angles close to the plane of the layers. This indicates that the electron orbits, whose orientation is strictly determined by the direction of the magnetic field $\mathbf{B}$, are changing with increasing angle in a way that they become more elongated in the p_z-direction. It follows that for magnetic field parallel to the thermal gradient, $\mathbf{B}\|\boldsymbol{\nabla}\Theta$, the interlayer conductivity σ_{zz} is maximum as $\bar{v}_z$ is maximum but the thermoelectric coefficient α_{xz} is zero since $\bar{v}_x$ is also zero. As field is rotated in the yz-plane, σ_{zz} decreases but α_{xz} increases as expected as the condition $\mathbf{B}\perp\boldsymbol{\nabla}\Theta$ is approached. Therefore, the NSLBAWs amplitude rapidly increases with increasing angle θ in a form of giant angular oscillations (as seen in fig. 4) for which the amplitude at the peaks significantly exceeds the zero amplitude observed at certain orientations of the magnetic field.

The NSLBAWs amplitude is suppressed at angles where $|\bar{v}_z|$ is zero or maximum as expected as it is conditioned mainly by the electrons drifting along the z-axis. For $\tan\theta > 1$ this occurs at angles $\theta_n^0 = \tan^{-1}(\frac{\pi\hbar}{cp_F}(n-\frac{1}{4}))$ and $\theta_n^{\max} = \tan^{-1}(\frac{\pi\hbar}{cp_F}(n+\frac{1}{4}))$, where $n = 1,2,3,\ldots$, is an integer. The NSLBAWs amplitude zeros appear at both of these angles, θ_n^0 and $\theta_n^{\max}$, that alternate consequently in the whole range of angles. This can also be interpreted in terms of how transport coefficients change with the angle θ. When $\bar{v}_z = \bar{v}_z^{\max}$ then the interlayer conductivity $\sigma_{zz}(\theta)$ is also maximum and when $\bar{v}_z$ is zero then $\sigma_{zz}(\theta)$ has a minimum at those angles. On the other hand, the thermoelectric coefficient $\alpha_{zx}(\theta)$ goes to zero, followed by a sign change, at angles where $\bar{v}_z$ is both maximum and zero as expected as $\alpha_{zx} \approx \tan\theta\frac{\partial\sigma_{zz}}{\partial\varepsilon}|_{\varepsilon=\mu}$. Maximum NSLBAWs amplitude is achieved at the mid-angle between two amplitude zeros, *i.e.*, at $\theta_n^{\mathrm{mid}} \approx \tan^{-1}(\frac{\pi\hbar}{2cp_F}(n+\frac{1}{2}))$. This estimate of the peak position of the NSLBAWs amplitude is correlated with the corrugated Fermi surface of the organic conductor; if the Fermi surface is extended in the interlayer direction, as it is in the organic conductor $\beta-(\mathrm{BEDT-TTF})_2\mathrm{IBr}_2$, a magnetic field applied at angle θ from the normal to the quasi-two-dimensional plane results in elliptical electron orbits on the Fermi surface in a plane perpendicular to magnetic field $\mathbf{B}$. The peaks in the angular dependence that correspond to a maximum wave generation at angles θ_n^{mid} are due to the electrons which interact most effectively with the wave whose velocity is half the maximum value of the averaged interlayer velocity at angles $\theta_n^{\max}$, $\bar{v}_z \approx \bar{v}_z^{\max}/2 = \frac{t_c}{\varepsilon_F}v_F$, implying that making complete closed trajectories is not necessary for the observation of the peaks in the angular oscillations of the NSLBAWs amplitude. In comparison, the DLBAWs are conditioned by the electrons with maximum averaged velocity along the z-axis, $\bar{v}_z = \bar{v}_z^{\max}$. It follows that for the thermal generation near the surface to be most effective it is not necessary for the electrons involved in the process to have a maximum averaged interlayer velocity as it is in the case of the DLBAWs generation. We suggest that this is due to the large local temperature gradient created by the thermal source situated at the surface that heats up the area near the surface where the NSLBAWs generation occurs. On the other hand, this indicates that the NSLBAWs will interact principally with electrons moving at different orbits near the surface of the conductor confined to the thermal skin layer depth δ_T including those that are in contact with the surface. In fact, not all of the extremal cross-section electrons interact effectively with the wave but only those for which the center of the classical orbit lies inside the conductor at a distance more than half the thermal skin depth δ_T in a magnetic field. These observations are different from those obtained for the DLBAWs which are governed primarily by the volume electrons who do not collide with the surface [5] as well as from those about SAWs where the orbits of the so-called skipping electrons that interact most effectively with the SAW intersect with the surface and their motion along trajectories is not periodic because of the diffuse reflection from the boundary [9,10]. An important difference between the NSLBAWs and DLBAWs is seen in the angular positions of the maxima, minima and amplitude zeros of the waves that arises from the different averaged interlayer velocity of the electrons involved in the process of thermal generation. Furthermore, we find that the amplitude of the NSLBAWs is by about ten times smaller than that of the DLBAWs. This is correlated not only with the smaller along the z-axis velocity of the electrons that interact most effectively with the wave but also with the smaller number of conduction electrons that take place in the NSLBAWs thermal generation.

The possible trajectories of the electrons that are involved in the NSLBAWs thermal generation in organic conductor $\beta-(\mathrm{BEDT-TTF})_2\mathrm{IBr}_2$ are presented in fig. 5. The orbits that belong to these electrons are those close to the surface in the thermal skin layer of a length δ_T. The most important electrons for the effect being studied are those whose interaction with the wave in a magnetic field has a resonance character ($\bar{v}_z \sim s$) and whose orbit centers are at distance $\delta_T/2 < z < \delta_T$ from the surface as revealed from fig. 3. This involves mainly electrons moving on orbits 1 and 2 in fig. 5. Some of the electrons moving only on orbit 1 (so-called glancing electrons) at a given magnetic field orientation, are in contact with the surface where they scatter elastically since the velocity ratio $\bar{v}_z/v_F \approx \bar{v}_z^{\max}/2v_F$ for these electrons is very small and is of order of the quasi-two-dimensionality parameter $t_c/\varepsilon_F \sim 10^{-2}$ of the organic conductor $\beta-(\mathrm{BEDT-TTF})_2\mathrm{IBr}_2$. Due to the elastic reflection from the surface their motion along the orbits is still periodic. At other orientations of the magnetic field the electron orbit can be close to but does not reach the

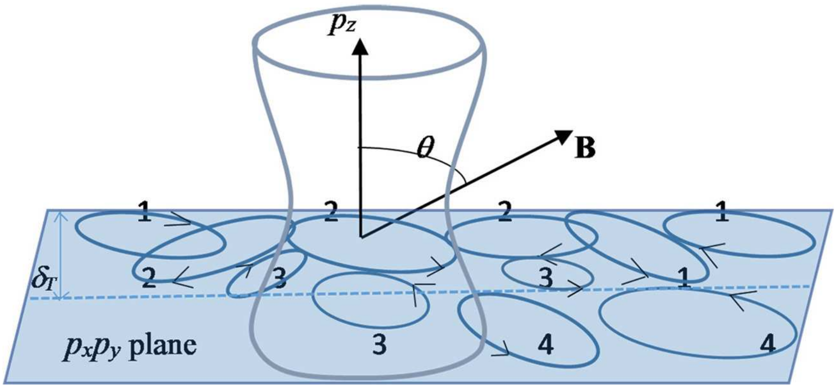

Fig. 5. Corrugated cylindrical Fermi surface of organic conductor $\beta-(\mathrm{BEDT}-\mathrm{TTF})_2\mathrm{IBr}_2$ open along the p_z-axis and projections of possible trajectories of surface and volume electrons in the p_xp_y-plane for different orientations θ of the magnetic field **B** from the normal to the crystal surface.

surface (orbit 2). The electrons on these orbits do not scatter from the surface and therefore move only along the given orbit without traversing to another one. However, due to the presence of a large temperature gradient $\nabla\Theta$ along the z-axis near the surface, at certain field orientations, electrons that belong to the orbits that are away from the surface whose centers are at distance $\delta_T/2 < z < \delta_T$ (fig. 5) in the thermal skin layer (smaller orbit 3) also take part in the NSLBAWs thermal generation thus dragging the acoustic field gradually into the bulk region of the conductor. The involvement of electrons moving on orbits distant from the surface in the NSLBAWs propagation allows for the waves not to attenuate fast after being generated (as is the case for the SAWs) as expected in agreement to the bulk nature of the NSLBAWs. In comparison, the thermal generation of DLBAWs is governed primarily by the volume electrons whose orbits are outside the thermal skin layer $z > \delta_T$ (larger orbit 3 and orbit 4).

Angular dependence of the NSLBAWs amplitude in fig. 4 reveals existence of two close to each other peaks with slightly different height at each magnetic field which become even closer with increasing angle. Our suggestion is that due to the scattering from the surface the electrons that move on orbit 1, at a given field orientation, instead of performing periodic motion on the same orbit (orbit 1) they transverse to another one (orbit 2) close to their original orbit but slightly larger in size (the different size orbits results from the corrugated Fermi surface of organic conductors) continuing to move with the same averaged interlayer velocity $\bar{v}_z$.

What is interesting in the angular dependence of the NSLBAWs amplitude is the apparent shift of the position of the first amplitude zero (around $\theta = 21°$–$25°$ in fig. 4 depending on the magnetic field strength) towards slightly higher angle for both thermal conditions with increasing field. However, there is no apparent shift of the positions of the higher order amplitude zeros. The absence of such a behavior in the angular dependence of the DLBAWs amplitude [5] suggest that the shift is due to the inhomogeneity of the acoustic field when magnetic field is rotated close to the normal to conductor's surface associated with its oscillating behavior at these angles (fig. 3). In addition, the shape of the angular oscillations of the waves is different due to the distinct type of electrons involved in their generation. Indeed, there are no amplitude zeros in the angular dependence of the DLBAWs amplitude at lower fields but there exist local maxima at higher fields. In the case of NSLBAWs the oscillation curves are similar in shape to each other independently on the magnetic field strength. Another difference involves the distinct position of the extremes in the angular dependence of the waves as mentioned above and hence, different period of oscillations. The peaks in the angular dependence of NSLBAWs repeat periodically in $\tan\theta$ with a period $\Delta(\tan\theta) = \frac{\pi\hbar}{2cp_F} = \frac{\pi\hbar}{cD_p}$ (where $D_p = 2p_F$ is the diameter of the Fermi surface along the p_x-axis) which is half the period of the angular oscillations of DLBAWs. This result is of great importance as it makes it possible to reveal fine details in reconstruction of the Fermi surface in organic conductors including determination of the closed electron orbits that cannot be obtain from studying the DLBAWs, SAWs or from the transport measurements.

3.4 Magnetic field dependence of the NSLBAWs amplitude

Figure 6 shows the dependence of the NSLBAWs amplitude in $\beta-(\mathrm{BEDT}-\mathrm{TTF})_2\mathrm{IBr}_2$ on the magnetic field B at $T = 20\,\mathrm{K}$ and $B(0) = 3\,\mathrm{T}$ for both thermal boundaries at different angles θ and distance $z = 0.5\,\mathrm{mm}$ from the conductor's surface.

It is evident that the magnetic field dependence of the NSLBAWs amplitude is quite different with chaining the angle θ, *i.e.*, depending on whether the magnetic field is close to the normal to the layers or near the layers plane in accordance with the observed angular behavior in fig. 4. Also, there is a profound change in the process of NSLBAWs generation with increasing magnetic field which is reflected as a change in the shape of magnetic curves. Obviously,

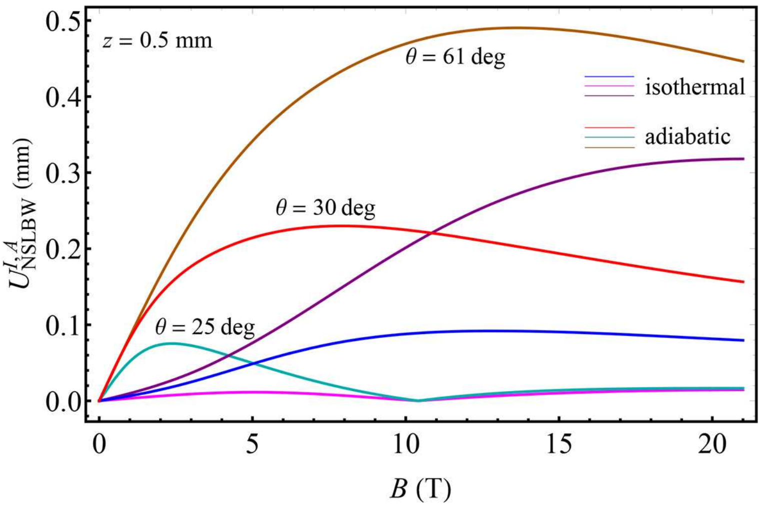

Fig. 6. The wave amplitude dependence on the magnetic field in the organic conductor $\beta-(\mathrm{BEDT}-\mathrm{TTF})_2\mathrm{IBr}_2$ for $T = 20\,\mathrm{K}$, $B(0) = 3\,\mathrm{T}$, $z = 0.5\,\mathrm{mm}$ and different field orientations: $\theta = 25^\circ, 30^\circ$ and 61° presented for both isothermal and adiabatic boundary. The blue, magenta and purple curves are for the isothermal condition while the red, cyan and brown curves are for the adiabatic boundary.

the amplitude is zero at zero magnetic field for both isothermal and adiabatic conditions, as expected, since thermal generation is a process that occurs only in the presence of an external magnetic field. With applying field the generation begins and the amplitude increases to a certain value with increasing field reaching a maximum at a different field, $B_i = B_i^{\max}$, which is angle dependent.

In fig. 6, three types of magnetic curves are presented which differ significantly with increasing angle θ. If the field is oriented closely to the normal to the layers and at the first amplitude zero in the angular dependence, $\theta_1^0 = 25^\circ$, then the NSLBAWs are generated with a small amplitude that decreases with increasing field (magenta and cyan curve). In this case a maximum efficiency in the generation is achieved at moderate fields, $B_{1,\mathrm{is}}^{\max} = 5\,\mathrm{T}$ for the isothermal and $B_{1,\mathrm{ad}}^{\max} = 2.4\,\mathrm{T}$ for the adiabatic boundary, respectively. What is characteristic for these field orientations is the fact that the amplitude becomes zero at relatively strong field around $11\,\mathrm{T}$ for θ_1^0. For this field, the conductor is acoustically transparent, a property which was already observed for the DLBAWs [5] but the difference is that for the NSLBAWs it occurs at much higher fields probably due to the fact that these waves are significantly affected by the presence of large temperature gradient $\boldsymbol{\nabla}\Theta$ that exists near the surface. This could be very useful as NSLBAWs can be utilized for designing filters with different polarization than those achieved with the DLBAWs that can find their purpose in the organic electronics. Our results show that, in organic conductors, wave processes are quite different allowing for many new possible applications in applied science.

With rotating the field away from the amplitude zeros angular positions the magnetic field dependence of the wave amplitude changes significantly. For $\theta = 30^\circ$ (blue and red curve) the amplitude increases continuously with increasing field reaching a maximum at higher field, $B_{2,\mathrm{is}}^{\max} = 12.8\,\mathrm{T}$ for the isothermal and $B_{2,\mathrm{ad}}^{\max} = 8\,\mathrm{T}$ for the adiabatic boundary. Similar behavior is observed at angels close to the plane of the layers such as for $\theta = 61^\circ$ (purple and brown curve) where the maximum wave generation is achieved at much stronger magnetic field, $B_{3,\mathrm{is}}^{\max} \sim 21\,\mathrm{T}$ for the isothermal and $B_{3,\mathrm{ad}}^{\max} = 13.6\,\mathrm{T}$ for the adiabatic boundary. Our results show that a maximum efficiency in the NSLBAWs generation does not occur at the same magnetic field for the isothermal and adiabatic boundary; it is obvious that not only the adiabatic NSLBAWs amplitude is larger than the isothermal one at each field direction but also the former reaches a maximum value at a lower field than the latter. This may be a manifestation of a number of causes including absence of a heat flux through the adiabatic boundary, a fixed value for the adiabatic temperature distribution Θ^A at $z = 0$ as well as distinct adiabatic and isothermal conductivity, $\sigma^A \sim \sigma^I - \alpha_{zx}^2$, when the thermoelectric coefficient α_{zx} is not small.

The observed behavior of NSLBAWs with magnetic field distinguishes these waves from DLBAWs in the organic conductor $\beta-(\mathrm{BEDT}-\mathrm{TTF})_2\mathrm{IBr}_2$. For the latter, there is a robust decrease of the amplitude after reaching a maximum value in a strong magnetic field for each field orientation except those that correspond to the amplitude zeros θ_n^0 [5]. For the former, these results are in agreement with the acoustic field distribution near the surface presented in fig. 3; the wave amplitude does not decrease with increasing distance z but rather maintains a steady value after reaching a maximum. Such a behavior of the NSLBAWs amplitude with the magnetic field, quite opposite of the DLBAWs amplitude behavior in this organic conductor, is because in a strong magnetic field oriented away from the direction normal to the layers almost all of the electrons on the Fermi surface which are in phase with the wave whose orbit centers are at a distance $\delta_T/2 < z < \delta_T$ from the surface are involved in the NSLBAWs generation to the contrary to the DLBAWs which are governed by part of the conduction electrons whose orbits are outside the thermal skin layer.

4 Conclusions

In summary, we have studied the generation of NSLBAWs in organic conductor $\beta-(\mathrm{BEDT}-\mathrm{TTF})_2\mathrm{IBr}_2$ in the presence of an external thermal source situated at the surface. Information concerning their properties is obtained through how the thermal and acoustic field distribution changes near the conductor's surface when these waves are generated as well as from their behavior in a magnetic field rotated from the direction normal to the layers towards the plane of the layers. Properties different from those specific for the DLBAWs are revealed as obtained from the comparison between the magnetic field and angular dependence of the waves amplitude. Our results show oscillating character of the NSLBAWs amplitude within the thermal layer, especially at lower fields and tilt angles, associated not only with the thermal source but also with the quasi-two-dimensional nature of the energy spectrum of the conductor. We find that almost all of the electrons whose orbit centers are within the thermal skin layer δ_T of the conductor take part in the wave generation but maximum efficient NSLBAWs thermal generation is achieved with the electrons that perform a periodic motion on closed orbits with a velocity that is half the maximum interlayer velocity for a given angle and whose orbit centers are at a distance $\delta_T/2 < z < \delta_T$ from the surface. As a result of the proximity of some of the electron closed orbits to the thermal source there are favourable conditions, arising from the existence of the temperature gradient, for some of the electrons to transfer to an orbit away from the surface at certain field strength and tilt angle; in that way the acoustic field of the NSLBAWs is dragged into the conductor. Compared to the DLBAWs in organic conductors, thermally generated NSLBAWs are characterized with smaller amplitude, different angular positions of the peaks and amplitude zeros in the angular dependence, two times smaller period of the oscillations, far larger amplitude in strong magnetic fields and larger tilts of the magnetic field. In addition, for the NSLBAWs the conductor becomes acoustically transparent at higher fields than those for the DLBAWs. This could make possible for a design of new filters with different wave polarization operable at strong magnetic fields for various applications in science and technology. Our results advance previous findings on thermal generation of bulk acoustic waves in organic conductors and stimulate further research on different wave processes in organic conductors. Studying the NSLBAWs will enable to determine the parameters of the Fermi surface of organic conductors which cannot be obtained from the DLBAWs or transport measurements. Furthermore, experimental investigation of the NSLBAWs will allow for construction of various electroacoustic devices based on crystalline organic materials, which possess more different properties than the conventional metals, for potential applications in organic electronics.

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