

Diamagnetism of Longitudinal Autosoliton in p -InSb in Longitudinal Magnetic Field

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Abstract

A longitudinal thermal-diffusion autosoliton generated in the non-equilibrium electron-hole plasma in p -InSb is shown to be diamagnetic in an external longitudinal magnetic field. The phenomenological estimate of the question allows deriving an expression for the magnetization, magnetic induction, and diamagnetic susceptibility of the autosoliton under an external magnetic field. Plots for these expressions, and computations and numerical estimations of the diamagnetism are performed.

Keywords

Autosoliton, Semiconductors, Non-Equilibrium, Dissipative Structure, Oscillations, Electron-Hole Plasma, Diamagnetism, Magnetic Field

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1. Introduction

It is known [1] that all materials are magnetic. Their huge variety occurs in nature. A main contribution into the magnetism is made by electrons revealing intrinsic resultant magnetic moments – spin, orbital. In an external magnetic field, spin magnetic moments are oriented in the direction of the field generating a paramagnetic magnetization, while orbital magnetic moments are directed against the field creating a diamagnetic magnetization. As for InSb, it can be referred to weakly magnetic materials.

Cr-compensated InSb-samples with carrier concentrations of $p \sim 10^{12} \text{ cm}^{-3}$ measured under a strong electric field [2, 3] exhibit a consistently high conductance triggered by autosolitons (AS) formed in a non-equilibrium and excited electron-hole plasma (EHP) generated by the joule heating in the electric field. AS is a steady isolated intrinsic stable state of a system, in our case, of non-equilibrium carriers in semiconductors and semiconducting structures. In other words, AS is localized areas of extreme carriers concentrations and their temperatures. The EHP generated by

the impact ionization, injection or traveling Gunn domain in GaAs thin films stratifies for current filaments and domains of electric field [4, 5, 6, 7]; longitudinal ASs are found in n -Ge in EHP photogenerated, warmed by the electric field [8]; space-time structures in the form of static and pulsing current filaments in p - i - n diodes are studied in works [9, 10]. The longitudinal autosoliton – the current filament implemented in p -InSb – we are interested in is a microlocalized region of enhanced carriers concentration and lower temperature (a cold AS) [11]. The estimation of autosoliton carriers concentration n_{AS} in studied samples gives a value of $n_{AS} \sim 10^{18} \text{ cm}^{-3}$, while the initial specific carriers concentration in the sample is $n = 10^{12} \text{ cm}^{-3}$. Facts pointed out allow to consider that the conductivity and all electrical physical properties of the sample may be substituted by AS and its behavior under an external influence.

2. Review Experimental Results

Due to the fact that in the cold AS [11], the carrier concentration is higher in the center than in the periphery, a

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diffusional outflow from AS center to the periphery happens. Since the electron mobility considerably exceeds the hole mobility $\mu_e \approx 100\mu_p$ [12] the diffusional flow of electrons from AS center to the periphery will occur and a region along an AS central axis will be hole-rich. In an external longitudinal magnetic field, the electrons of this flow will start to rotate in spiral around the hole-enriched central area and simultaneously the electrons are involved in an ambipolar drift together with holes in the electric field applied to the sample.

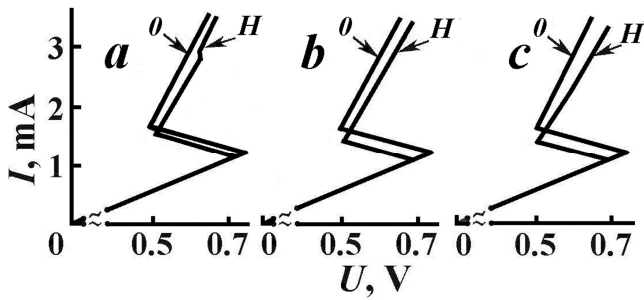


Fig. 1. Dynamic voltage-current characteristics of *p*-InSb at constant values of the applied longitudinal magnetic field: a – $H_1 = 2.4 \cdot 10^4$ A/m, b – $H_2 = 3.7 \cdot 10^4$ A/m, c – $H_3 = 6.2 \cdot 10^4$ A/m.

If we regard each turn of the spiral as an electron orbit around the positively charged center we could liken the indicated orbit to the electron orbit in atom. All orbits in AS in the longitudinal magnetic field are parallel to each other; lie in a plane perpendicular to the current and magnetic field directions. Possessing the orbital magnetic moment the turns define a total magnetic moment of the AS M_{AS} . Summing up, we can conclude that the longitudinal AS becomes a diamagnet in the external longitudinal magnetic field. The experimental investigations on a behavior of AS current in Cr-compensated *p*-InSb under the longitudinal magnetic field show the voltage-current characteristics exhibiting the formation of AS and a change in the current with increase in the electric field to be different from the voltage-current characteristics (VCC) obtained at the external longitudinal magnetic field (Fig. 1). The AS current change in the magnetic field occurs at lower values than in the absence of that. When increasing the magnetic field, the difference of the current change on VCC rises. As is evident from Fig.1, a change in the sample conductivity in the longitudinal magnetic field does not occur in the ohmic region, i.e. when the AS lacks. In the case of AS presence (the non-linear region of VCC), the change of the sample conductivity or the AS current under the longitudinal magnetic field is associated with a change either in AS carriers concentration or in carriers mobility. A decrease in the longitudinal current with the increase of the longitudinal magnetic field is caused, on the one hand, by a fall in the mobility because of the path curvature of radially moving electrons, on the other hand, by

a decrease in the mobility in accordance with $\mu \sim 1/n$ for a densifying initial plasma as a result of the current filament compression in the longitudinal magnetic field. And the carrier concentration in AS remains unaltered, but the specific concentration of carriers in AS changes due to the variation of an AS transversal size.

Work [13] reported that the longitudinal AS implemented in *p*-InSb can move in the Lorentz force direction at application of transversal magnetic field to the sample. Works [14, 15] reported that the longitudinal AS formed in the non-equilibrium EHP in *p*-InSb moves in the direction of the sample periphery under the influence of the transversal magnetic field. On the other hand, it is experimentally shown [16] that the flow of the current filament in samples realized in the transversal magnetic field with a simultaneous effect of the longitudinal magnetic field fails. Put it in other words, the galvanomagnetic Ettingshausen effect appeared in the longitudinal AS in the longitudinal magnetic field inducing a AS flow in the sample is entirely blocked by the diamagnetism occurred in AS in the external longitudinal magnetic field.

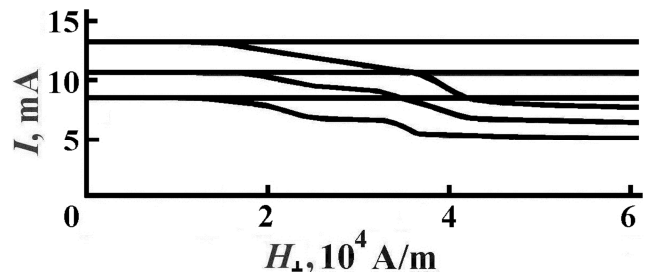


Fig. 2. Gauss-ampere characteristics for different currents of the longitudinal AS under the transversal magnetic field in the absence and presence of the longitudinal magnetic field $H_{||} = 7.2 \cdot 10^4$ A/m = const.

Fig. 2 exhibits dependences of three different currents of the longitudinal AS on the transversal magnetic field H_{\perp} (Gauss ampere characteristics – GAC) with the longitudinal magnetic field (straight lines) and without that (curve lines).

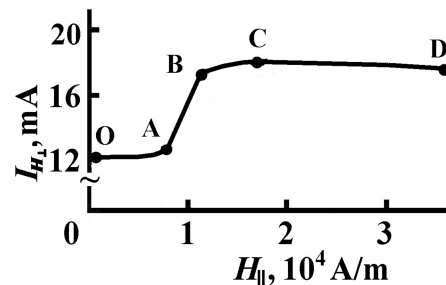


Fig. 3. Dependence of the longitudinal AS current under transversal magnetic field $I_{H_{\perp}}$ on the longitudinal magnetic field $H_{||}$.

As is evident from Fig. 2, the longitudinal AS current in the transversal magnetic field does not vary at a simultaneous effect of the constant longitudinal magnetic field. In the

absence of the longitudinal magnetic field, the influence of the transversal magnetic field on the longitudinal AS current is essential [14, 16].

Fig. 3 demonstrates the dependence of AS current in the specified transversal magnetic field

$I_{H\perp}$ ($H_{\perp} = \text{const}$) with a change in a longitudinal magnetic field value GAC. As is evident from Fig. 3, when increasing the longitudinal magnetic field the $I_{H\perp}$ smoothly rises (OA segment) first and then abruptly jumps (AB segment) with a following transition for saturation or even decreasing (CD segment). The OA segment indicates a linear slowing-down in the AS flow in the transversal magnetic field. The AB segment – the abrupt positive jump of the current – testifies to a sharp slowing-down and a failure of the current filament flow. The BD segment shows a change in the AS current to be occurred only under the longitudinal magnetic field though the transversal magnetic field presents.

The observed effect is implemented due to simultaneous realization of two phenomena considered in works [13, 14, 17]. As works [13, 14] depict, the current filament gains a temperature gradient in the Lorentz force direction under the influence of the transversal magnetic field by reason of the Ettingshausen effect. It is this temperature gradient that provides the transfer of the AS in the direction of the sample periphery characterized by a low temperature. In the dependence of transversal dimensions of the sample the AS achieves a sample boundary or such a temperature region where the longitudinal AS vanishes. It is experimentally observed a sharp decrease in the current or the instability of the longitudinal AS. On the other hand, in the longitudinal magnetic field, the longitudinal AS becomes a diamagnet, i.e. it is a cylinder consisting of electron path spirals moving around the hole-enriched region generating a self-magnetic field [17]. Spinning electrons are able to the heat transport from a hot current filament to a cold one. The higher the longitudinal magnetic field is, the faster the electrons spin, and the greater the heat transport is. Consequently, the temperature gradient difference of current filament fronts provided the flow of current is smoothed, what causes the slowing of the filament. The temperature gradient in the current filament disappears at a certain sufficient value of the longitudinal magnetic field and, consequently, the current filament fails to drift though the same transversal magnetic field presents. So, the Ettingshausen effect is blocked by the longitudinal magnetic field.

3. Phenomenological Consider, Results and Discussion

It can be suggested the longitudinal AS will change into the

diamagnet in the longitudinal magnetic field of a minimum value H_0 when the cyclotron radius r of electron spinning diffusing in the transversal direction with respect to the hole-rich region will be equal to an electron diffusion length L_e , i.e. $r = L_e = m_e v_d / \mu_0 e H_0$, $v_d = 2\pi L_e / \tau_e$. We obtain $\tau_e = 2\pi m_e / \mu_0 e H_0$, $f = \mu_0 e H_0 / 2\pi m_e$, where v_d is the electron diffusive drift rate, τ_e is the time of electron one turn in an orbit or the electron lifetime, f is the rate of electron orbital rotation, μ_0 is the magnetic permeability of the vacuum. When a value of the longitudinal magnetic field is $H_0 = 2\pi m_e / \mu_0 e \tau_e$, the longitudinal AS is a cylinder consisting of electron path spirals spinning around the hole-enriched region generating a self-magnetic field. Fig. 4 presents the oscillograms of dependences differing by initial values of AS currents from the longitudinal magnetic field applied to the sample as triangular impulse – the dynamic GAC. The determination of a minimum magnetic field H_0 at which the AS is changed into the diamagnet is the goal of the creation of such GAC. Measurements made using this and other methods provide the value of the magnetic field $H_0 \approx 2000$ A/m. We obtain the value of AS electron lifetime $\tau = 2\pi m_e / \mu_0 e H_0$ from known expression for $\tau_e = 4.3 \cdot 10^{-10}$ s. This value is close to the results obtained in [12]. Let's consider each spiral turn as the orbit of electron motion in the atom. All orbits are mutually parallel and perpendicular to the direction of the external magnetic field. Possessing the magnetic moment M_e the turns define the total magnetic moment of AS.

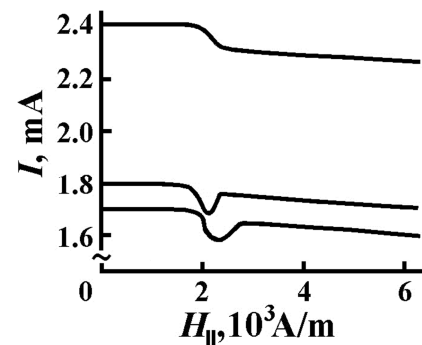


Fig. 4. Gauss-ampere characteristics for different currents of the longitudinal AS under the longitudinal magnetic field.

$M_{AS} = \Sigma^n M_n = n M_e$, where M_e is the magnetic moment of a turn, n is the number of turns. The magnetic moment of an electron spinning around the hole with the rate f will be: $M_e = -I_e S = -efS$, where $S = \pi L_e^2$ is the area of an electron turn.

$$M_e = -\mu_0 e^2 L_e^2 H_0 / 2m_e \quad (1)$$

The magnetic moment direction of a turn generated by the spinning of radially moving electron in the AS under the external longitudinal magnetic field is shown in Fig. 5. When the direction of the external magnetic field is such as shown in Fig. 5a, the Lorentz force, in accordance with the left-hand

rule, is directed in such a way that a circular current triggered by the electron rotation flows in a clockwise order, what, in compliance with the right-hand screw, provokes the appearance of the magnetic moment oppositely directed to the external magnetic field. A change in the direction of the external magnetic field H_0 into the opposite (Fig. 5b) entails the variation of the turn magnetic moment. So, the directions of induced magnetic moment M_e in AS and the external magnetic field, as could be expected, are oppositely directed.

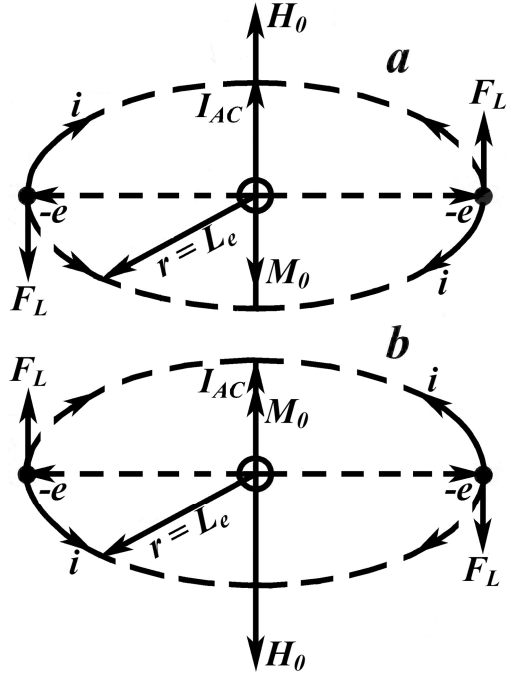


Fig. 5. The appearance of the diamagnetism in the longitudinal AS under external longitudinal magnetic field H_0 .

Radii of spinning electrons will be $0 \leq r \leq L_e$ by virtue of the spread of diffusing electron directions. Let's change this inequality with the concept of the average radius of spinning electrons. We consider an AS cell with sizes as follows: a cell radius is $r = L_e$, a cell height is $h = L_e$. The volume of the cell is $v = \pi L_e^3$. The number of electrons in the cell is $n_e = n_e v = \pi L_e^3 n_e$, n_e is the specific concentration of electrons in AS. The unit radius of a spinning electron in this cell is $r_k = L_e \cos \alpha_k$, where α_k is the angle between the diffusing electron direction and the plane perpendicular to the AS current direction. The number of turns k can be taken as the number of electrons since we allow for only the number of electrons irrespective of the orbit number, i.e. $k = n_e$. $\alpha_k = m(\pi/2k)$, where m is a direction number from 0 to k , $\sum_{m=0}^k m(\pi/2k) = \pi/2$. Averaged radius is $\bar{r} = (\sum r_k) / k = L_e [\sum_{m=0}^k \cos m(\pi/2k)] / k$. Numerical calculations $[\sum_{m=0}^k \cos m(\pi/2k)] / k$ yield a value of 0.637, whence it follows $\bar{r} = 0,637L_e$. The magnetic moment of spinning electrons for the considered cell is $M_c = M_e n_e = -(\mu_0 e^2 \bar{r}^2 H_0 / 2m_e) \pi L_e^3 n_e = -0.2\pi\mu_0 e^2 L_e^5 n_e H_0 / m_e$. The magnetic moment of spinning electrons for all AS is:

$$M_{AS} = M_c \cdot (l/L) = -0.2\pi\mu_0 e^2 L_e^4 l n_e H_0 / m_e \quad (2)$$

A magnetization J_0 of AS gets:

$$J_0 = M_{AS} / v = M_{AS} / \pi L_e^2 l = -0.2\mu_0 e^2 L_e^2 n_e H_0 / m_e = -0.2\alpha H_0, \quad (3)$$

Where $\alpha = \mu_0 e^2 L_e^2 n_e / m_e$

A magnetic induction of AS becomes:

$$B_0 = H_0 + J_0 = (1 - 0.2\alpha)H_0 \quad (4)$$

Let's take $1 - 0.2\alpha = \mu_{AS}$, where μ_{AS} is the magnetic permeability of AS.

We write $B_0 = \mu_{AS} \cdot H_0$.

An additional diamagnetic moment of electrons appeared at the application of the external magnetic field to spinning electrons is [18]:

$$M_e^d = -\mu_0 e^2 r^2 B_0 / 4m_e \quad (5)$$

In case of $H = H_0$ $r = L_e$. However, the spinning electron radii are $r_k = L_e \cos \alpha_k$ because of the spread of diffusing electron directions. Since the angular rate variation of the electron turn in the orbit is similar for all electrons irrespective of their orbit radii and linear travel we can employ the concept of the averaged radius. Following the preceding reasoning and allowing for the unit cell with a height of $h = L_e$, a square of $S = \pi L_e^2$, we change r_k into the averaged radius $\bar{r} = 0,637 L_e$. We yield: $M_c^d = -0.4\mu_0 e^2 L_e^2 n_e B_0 / 4m_e = (-0.4\mu_0 e^2 L_e^2 B_0 / 4m_e) \pi L_e^3 n_e = -0.1\pi\mu_0 e^2 n_e L_e^5 B_0 / m_e$. The diamagnetic moment of spinning electrons for whole AS becomes:

$$M_{AS}^d = M_c^d (l/L_e) = -0.1\pi\mu_0 e^2 L_e^4 l n_e B_0 / m_e \quad (6)$$

Determine the diamagnetic moment per AS unit volume, i.e. a diamagnetic magnetization J_d of AS. It will be equal to the quotient of the whole AS induced diamagnetic moment and the AS volume $v = \pi L_e^2 l$.

$$J_d = M_{AS}^d / v = -0.1\mu_0 e^2 L_e^2 n_e B_0 / m_e = -0.1\alpha B_0 \quad (7)$$

A magnetic susceptibility for the diamagnetic effect of AS is evaluated by an expression:

$$\chi_d = J_d / B_0 = -0.1\alpha \quad (8)$$

At the outset of the presentation, we suggest the physical nature of the AS diamagnetism is similar to the nature of the diamagnetism atom like an electron systems moving around the nucleus in specified closed orbit. For simplicity, it is usually assumed that one electron moves in an orbit with an angular rate $\omega = 2\pi f$. If the magnetic field is applied to spinning electron, the angular rate varies and the orbital radius remains unaltered. A change in the angular rate leads just to the generation of the magnetic moment M_d and

motivates always negative susceptibility.

We get expressions for the AS magnetic moment (2), AS magnetization (3), AS diamagnetic moment (6), diamagnetic magnetization (7), and AS diamagnetic susceptibility (8) in the longitudinal magnetic field at such a value of H_0 , when the cyclotron radius of electron spinning becomes equal to the diffusion length L_e and the turn of spinning electrons appears as a closed cycle. The Larmor radius of the electron spinning will decrease with an increase in the longitudinal magnetic field strength. One can find such a value of the magnetic field H_2 , at which we obtain two closed cycles at the electron diffusion length L_e during the lifetime of electron τ_e : $2\pi L_e = 2\pi r_2 + 2\pi r_2$, where $r_2 = L_e / 2$. It is known, $r_2 = m_e v_d / eH$, $v_d = 4\pi r_2 / \tau_e = 4\pi L_e / 2\tau_e$. From the condition of the cycle closeness we derive: $r_2 = 4\pi m_e r_2 / e\tau H_2$, $H_2 = 4\pi m_e / e\tau_e = 2H_0$. Write the expression (1) at a value of the magnetic field strength $H_2 = 2H_0$, when $L_e = 2r_2$: $M_e = -\mu_0 e^2 \cdot r_2^2 H_2 / 4m_e = -\mu_0 e^2 (L_e^2 / 2^2) \cdot 2H_0 / 4m_e = -\mu_0 e^2 L_e^2 2H_0 / 2^2 4m_e$. Further increasing of the longitudinal magnetic field strength produces the occurrence of three, four, n cycles of the electron spinning in the AS, and correspondingly, we get:

$$M_{en} = -\mu_0 e^2 L_e^2 n H_0 / n^2 4m_e = -\mu_0 e^2 L_e^2 H_0^2 / H_n \cdot 4m_e \quad (1')$$

The values of the magnetic field strength are: $H_n = nH_0$, $n = 1, 2, 3 \dots n$.

Correspondingly, an expression for M_{ASn} is:

$$M_{ASn} = -0.2\pi\mu_0 e^2 L_e^4 l n_e H_n / n^2 m_e = -0.2\pi\mu_0 e^2 L_e^4 l n_e H_0^2 / H_n m_e = (-0.2\pi\mu_0 e^2 L_e^4 l n_e H_0^2 / H_n^2 / m_e) H_n \quad (2')$$

The AS magnetization becomes:

$$J_n = M_{ASn} / v = -0.2\mu_0 e^2 L_e^2 n_e H_0^2 / H_n m_e = -0.2\alpha H_0^2 / H_n = (-0.2\alpha H_0^2 / H_n^2) \cdot H_n \quad (3')$$

The magnetic induction is written as:

$$B_n = H_n + J_n = (1 - 0.2\alpha H_0^2 / H_n^2) H_n = \mu_{ASn} H_n \quad (4')$$

Where $\mu_{ASn} = 1 - 0.2\alpha H_0^2 / H_n^2$

The electron diamagnetic moment in AS at $H = H_n$ is:

$$M_{en}^d = -\mu_0 e^2 (L_e/n)^2 B_n / 4m_e \quad (5')$$

$$M_{cn}^d = -0.4\mu_0 e^2 (L_e/n)^2 n_c B_n / 4m_e = -0.1\mu_0 e^2 L_e^2 \cdot \pi L^3 n_e B_n / n^2 m_e = -0.1\pi\mu_0 e^2 L_e^5 n_e B_n / n^2 m_e$$

The diamagnetic moment of the whole AS at $H = H_n$ is expressed as:

$$M_{ASn}^d = M_{cn}^d \cdot l / L_e = -0.1\pi\mu_0 e^2 L_e^4 l n_e B_n / n^2 m_e \quad (6')$$

The diamagnetic magnetization becomes:

$$J_n^d = M_{ASn}^d / \pi L^2 l = -0.1\mu_0 e^2 L_e^2 n_e B_n / n^2 m_e =$$

$$-0.1\alpha \cdot B_n / n^2 \quad (7')$$

The diamagnetic susceptibility in this case is defined by an expression:

$$\chi_n = J_n^d / B_n = -0.1\alpha / n^2 \quad (8')$$

For each AS the n_e is a particular value. The specific carriers concentration in the longitudinal AS can be derived from $n_{AS} = I_{AS} l / Se\mu_a V$ ($I_{AS} = jS = Sen_{AS}\mu_a E$), where I_{AS} is the AS current, l is the sample length, $S = \pi L_e^2$ is the area of AS transversal section, $V = lE$ is the electric field strength applied to the sample, μ_a is the ambipolar mobility of carriers. $\mu_a = 2\mu_e(\mu_e + \mu_p)$, $\mu_e \approx 100\mu_p$, then $\mu_a = 2\mu_p$. Consequently, $n_{AS} = I_{AS} l / 2Se\mu_p V$. The specific carriers concentration involving in the AS conductivity is $n_e = n_{AS} / 2 = I_{AS} l / 4Se\mu_p V$. In accordance with that, the magnetic moment of the cell is: $M_c = -\mu_0 e L_e^3 l I_{AS} H_0 / 20\mu_p V$. The magnetic moment for the whole AS is:

$$M_{AS} = M_c \cdot (l / L_e) = -\mu_0 e L_e^2 l^2 I_{AS} H_0^2 / H_n 20m_e \mu_p V \quad (2'')$$

Then the AS magnetization is equal to:

$$J_n = M_{AS} / v = -\mu_0 e l I_{AS} H_0^2 / H_n 20\pi m_e \mu_p V = -0.2\mu_0 e l I_{AS} H_0^2 / H_n 4\pi m_e \mu_p V \quad (3'')$$

With $n_e = I_{AS} l / 4Se\mu_p V$, in mind, the previous expression can be written as: $J_n = (-0.2\alpha H_0^2 / H_n^2) H_n$, where $\alpha = \mu_0 e l I_{AS} l / 4\pi m_e \mu_p V = \mu_0 e^2 L_e^2 n_e / m_e$.

We have: $\mu_0 = 4\pi \cdot 10^{-7} \text{ kg} \cdot \text{m} / \text{k}^2$, $e = 1.6 \cdot 10^{-19} \text{ k}$, $L_e = 10^{-3} \text{ cm} = 10^{-5} \text{ m}$, $l = 0.05 \text{ cm} = 5 \cdot 10^{-4} \text{ m}$, $I_{AS} = 8.7 \cdot 10^{-3} \text{ A}$, $m_e = 0.03 \cdot 9.1 \cdot 10^{-31} \text{ kg}$, $\mu_p = 1694 \text{ cm}^2 / \text{V} \cdot \text{s} = 0.1694 \text{ m}^2 / \text{V} \cdot \text{s}$, $V = 0.97 \text{ V}$. The calculations of expressions for the AS magnetization J_n (3'), AS magnetic induction B_n (4'), diamagnetic magnetization J_n^d (7') and diamagnetic susceptibility (8') yield following values at $H_l = H_0 = 2000 \text{ A/m}$ ($n = 1$), $J_l = -6.2 \cdot 10^3 \text{ A/m}$, $B_l = -4.8 \cdot 10^3 \text{ A/m}$, $J_l^d = 6.5 \cdot 10^3 \text{ A/m}$, $\chi_l = -1.56$. The evaluation of the expression for the AS magnetic induction $B_0 = (1 - 0.2\alpha) H_0$ shows that it becomes equal to zero at $n_e = 4.25 \cdot 10^{16} \text{ cm}^{-3}$, i.e. the value of the induced magnetic field in the AS achieves the value of the external magnetic field H_0 . It should be noted, however, the existence of AS is failure at such a concentration of electrons. When increasing the applied magnetic field H_n the AS magnetization J_n fast falls ($\sim 1/n$), Fig. 6a, the AS magnetic induction B_n first decreases in the range of negative values, Fig. 6b, passes the zero value at $n = 0.2\alpha$ when the magnetic permeability is $\mu_{ASn} = 0$, next increases with a value close to H_n , since $\mu_{ASn} \rightarrow 1$. When increasing the external magnetic field H_n , the AS magnetic magnetization J_n^d first rapidly decreases ($\sim 1/n^3$) in the positive value range and tends to the zero in the negative range ($\sim 1/n$), Fig. 6c. The derived

considerable value for the AS diamagnetic susceptibility ($\chi = -1.56$ at $H = H_0$) is caused by a large dimensions of electron spin orbits ($r \sim 10^{-3}$ cm), in the longitudinal magnetic field. Nevertheless, the AS diamagnetic susceptibility conditioned on the magnetic field (8'), rather quickly decreases ($\sim 1/n^2$) with a rise in the magnetic field H_n , Fig. 6d, and at $H_n \approx 7.96 \cdot 10^5$ A/m becomes comparable to the diamagnetic susceptibility ($\chi \sim 10^{-5}$) of a regular magnetic.

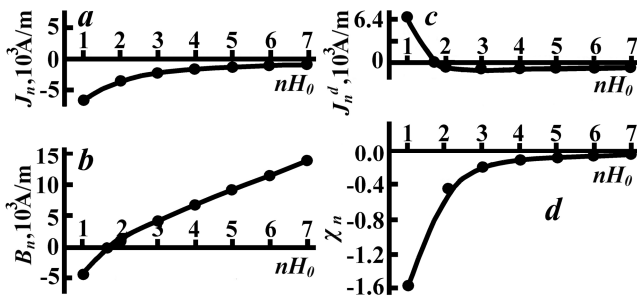


Fig. 6. Characteristics of longitudinal AS magnetic properties under external longitudinal magnetic field nH_0 ($H_0 = 2000$ A/m).

4. Conclusions

So, the longitudinal thermodiffusion AS formed in the non-equilibrium electron-hole plasma in *p*-InSb under the external longitudinal magnetic field is shown to gain diamagnetic properties. The point of departure for this statement is the diffusion of electrons for considerable distance from the axis of AS current filament stemmed from a high mobility in regard to holes in the thermodiffusion AS. In the longitudinal magnetic field, the electrons spin around the central hole-enriched region forming the closed orbits and create the magnetic moment M_e . All orbits are mutually parallel and in total define the general magnetic moment of the whole AS $M = \sum M_e$.

The phenomenological treatment of the problem allows obtaining the expressions as follows:

The AS magnetization in the external magnetic field:

$$J_n = (-0.2\alpha H_0^2 / H_n^2) \cdot H_n;$$

The AS magnetic induction in the external magnetic field:

$$B_n = (1 - 0.2\alpha H_0^2 / H_n^2) H_n = \mu_{ASn} H_n;$$

The AS diamagnetic magnetization in the external magnetic field:

$$J_n^d = -0.1\alpha \cdot B_n / n^2;$$

The AS diamagnetic susceptibility in the external magnetic field:

$$\chi_n = J_n^d / B_n = -0.1\alpha / n^2,$$

where $\alpha = \mu_0 e^2 L_e^2 n_e / m_e = \mu_0 e I_{AS} / 4\pi m_e \mu_p V$.

The computation of the diamagnetic susceptibility χ_n and its estimation provide the large value of $\chi = -1.56$ at H_0 , primarily, stemmed from large dimensions of electron spinning orbits ($r \sim 10^{-3}$ cm), in the AS in the longitudinal magnetic field. Though, when increasing the external magnetic field H_n , the orbit radii vigorously decrease what leads to the same decreasing ($\sim 1/n^2$) in the diamagnetic susceptibility.

References

- [1] S.V. Vonsovskii. Magnetizm. Izdatel'stvo «Nauka», Moscow, 1971, p.1032.
- [2] A.A. Stepurenko, Fiz. Tekh. Poluprov. 28, 402 (1994).
- [3] A.A. Stepurenko, Fiz. Tekh. Poluprov. 30, 76 (1996).
- [4] B.S. Kerner and V. V. Osipov, Sov. Phys. JETP 36, 359 (1982).
- [5] V.A. Vashchenko, B.S. Kerner, V.V. Osipov and V.F. Sinkevich. Fiz. Tekh. Poluprov., 23, 1378 (1989).
- [6] T. Hayashi, T. Morita, M. Fukaya and E. Hasegawa. Japan J. Appl. Phys., 13. № 10. 1667 (1974).
- [7] B.S. Kerner, V.V. Osipov, M.T. Romanko, V.F. Sinkevich. Sov. Phys. JETP, 44, v. 2, 77 (1986).
- [8] M.N. Vinoslavskii. Fiz. tverd. Tela., 31, 315 (1989).
- [9] R. Symanczyk, E. Pieper and D. Jäger. Phys. Lett. A, 143, 337 (1990).
- [10] R. Symanczyk, S. Gaelings and D. Jäger. Phys. Lett. A, 160, 397 (1991).
- [11] I.K. Kamilov, A.A. Stepurenko and A.S. Kovalev. Fiz. Tekh. Poluprov., 36, 187 (2002).
- [12] C. Hilsum and A. C. Rose-Jnnes, Semiconducting III – V Compounds., Pergamon Press. Oxford / London / New York / Paris. 1961, (p.323).
- [13] A.K. Zvezdin and V.V. Osipov. JETP, 58, 160 (1970).
- [14] I.K. Kamilov, A.A. Stepurenko, A.E. Gummetov and A.S. Kovalev. Fiz. Tekh. Poluprov., 42, 393 (2008).
- [15] I.K. Kamilov, A.A. Stepurenko, A.E. Gummetov and A.S. Kovalev. Fiz. Tekh. Poluprov., 41, 286 (2007).
- [16] I.K. Kamilov, A.A. Stepurenko and A.E. Gummetov. Fiz. Tekh. Poluprov., 45, 456 (2011).
- [17] I.K. Kamilov, A.A. Stepurenko and A.E. Gummetov. Fiz. Tekh. Poluprov., 44, 721 (2010).
- [18] YU.K. Shalabutov. Vvedeniye v fiziku poluprovodnikov. Izdatel'stvo «Nauka», Leningrad, 1969, p.292.