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1998 J. Phys.: Condens. Matter 10 9477

(http://iopscience.iop.org/0953-8984/10/42/013)

J. Phys.: Condens. Matter **10** (1998) 9477–9483. Printed in the UK PII: S0953-8984(98)92040-9

Autosolitons in InSb in a low magnetic field

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Received 24 February 1998, in final form 14 July 1998

Abstract. It is shown experimentally that a relatively low applied longitudinal magnetic field causes a noticeable change in the velocity of autosoliton travel in InSb samples and a redistribution of these autosolitons in the electric field. As a result, the current oscillation frequency and amplitude in the external circuit of the sample either increase or decrease depending on direction of the magnetic field.

1. Introduction

The theoretical investigations of B S Kerner and V V Osipov [1–4] showed that thermodiffusal autosolitons (ASs) can be excited in a heated electron–hole plasma (EHP) by applying an additional external perturbation. In a dense EHP, in the presence of external electric field, the ASs manifest themselves as current sheets directed along the applied electric field [5, 6] while in an EHP of lower density the ASs are formed as strong electric field layers oriented normally to the lines of current [5, 7].

It is shown in [8–10] that the nonequilibrium EHP in n-GaAs, formed by collision ionization or injection, separates into numerous current filaments and electric field domains in a high electric field. Experimental detection and investigation of a hot moving AS in a homogeneously photogenerated EHP heated by the electric field in n-Ge are given in [11].

It was shown in [12] and [13] that in nonequilibrium EHP excited in InSb by Joule heating, in a high electric field, the ASs are excited either in the form of current sheets or in the form of strong electric field domains. This is in agreement with the experimental results obtained in [8–10]. Since the EHP in InSb is highly asymmetric ($m_p^* \gg m_e^*$), the strong electric field domains travel in the electric field along current layers, just like hot electrons do, i.e. from cathode to anode, stimulating current oscillations in external circuits of the sample. The form and velocity of the ASs which travel in this case are similar to those described in [11]. It was also shown in [13] that two main types can be chosen from the multiple current oscillations. Each mode is characterized by its appropriate applied voltage range. For the first type (type I) the frequency of oscillations decreases and the amplitude increases as voltage increases, while for the other (type II) the frequency increases gradually and there is a maximum in the amplitude curve.

The ASs in the InSb samples should be quite sensitive to a magnetic field [14]. As the ASs present the local regions of the gradients of carrier concentration and temperature [12, 13], the influence of magnetic field on them is most likely associated with the thermomagnetic Nernst–Ettingshausen effects [14].

0953-8984/98/429477+07$19.50

2. Experimental details

We present in this paper a study of ASs in InSb samples placed in a longitudinal magnetic field. The sample to measure was placed into a solenoid; the maximum magnetic field reached 10^4 A m^{-1}. InSb samples of various sizes with hole densities $p = (2\text{–}4) \times (10^{12}$ cm^{-3} and carrier mobilities $\mu \approx 4000$ cm^2 V^{-1} s^{-1} were measured at $T = 77$ K. In the present paper the experimental results for samples of InSb B1 with sizes $0.5 \times 0.19 \times 0.13$ cm^{-3}, resistance $R_1 = 7.9$ kΩ and InSb A2B4 with sizes $0.59 \times 0.2 \times 0.12$ cm^3, resistance $R_2 = 8.7$ kΩ are given. The used magnetic field was low both for holes ($\mu_p H/c \approx 5 \times 10^{-3}$), and for electrons ($\mu_e/\mu_p \sim 100$; $\mu_e H/c \approx 0.5$). A nonequilibrium EHP in the samples was created by Joule heating resulting from the rectangular electric voltage pulses applied with durations of up to 1 ms and repetition frequency of the order of 10 Hz. The created EPH was excited by the same electric voltage pulses, and therefore ASs arose, taking the form of current sheets in hot and dense areas of EPH ($\mu \sim T^{3/2}/n$), and as travelling layers of a strong electric field in cooler and less dense areas of EPH [13]. The resistance of samples in the presence of ASs became $R_1^{AS} = 5.5\text{–}3.5$ kΩ, $R_2^{AS} = 6\text{–}3$ kΩ depending on the level of excitation. The influence of a longitudinal magnetic field on the travelling ASs was investigated [13]. The magnetic field was switched on only if current oscillations had been generated in the external circuit of the sample.

3. Experimental results

Figure 1 shows the oscillograms of current oscillations for mode I for parallel (a) and antiparallel (b) orientation of $\boldsymbol{H}$ and $\boldsymbol{E}$ and the dependences of the oscillation frequency (c) and amplitude (e) magnetic field applied within the range from 0 to 1500 A m^{-1}.

With the magnetic field parallel to the electric field $\boldsymbol{H} \uparrow\uparrow \boldsymbol{E}$ (figure 1(d)), a decrease in the oscillation frequency with an increase in magnetic field intensity is observed. Curves 1, 2 and 3 correspond to three different values of voltage pulses $U_1 < U_2 < U_3$ applied to the sample at which oscillations are generated. The oscillations differ in frequencies and amplitudes and were traced from those points.

With antiparallel directions of the magnetic and the electric field $\boldsymbol{H} \downarrow\uparrow \boldsymbol{E}$ (figure 1(d)) the frequency of the oscillations changes in a different way (curves 1′, 2′ and 3′ in figure 1(c). At the minimum initial voltage U_1 (figure 1(c)), curve 1′), the oscillation frequency decreases slightly with magnetic field increase, then passes three extrema and begins to increase slightly. At a larger initial voltage U_2 (figure 1(c), curve 2′), the oscillation frequency increases gradually with magnetic field increase, then passes two extrema maintaining further the tendency to increase. At the maximum initial voltage U_3 (figure 1(c), curve 3′), the oscillation frequency increases all the time the magnetic field increases.

Figure 1(e) shows the dependences of the current oscillation amplitude on the magnetic field intensity at the same initial voltages $U_1 < U_2 < U_3$ applied to the sample. The amplitude of oscillations increases gradually when $\boldsymbol{H} \uparrow\uparrow \boldsymbol{E}$ (curves 1, 2 and 3 in figure 1(e)) and decreases gradually when $\boldsymbol{H} \downarrow\uparrow \boldsymbol{E}$ (curves 1′, 2′ and 3′ in figure 1(e)).

In the case of $\boldsymbol{H} \uparrow\uparrow \boldsymbol{E}$, the frequency and amplitude of current oscillations varied with the magnetic field increase similarly to the electric voltage increase (figure 1(f), (g), curves 0, 0). Figure 1 also shows the plots of the current oscillation frequency f (curves 1′, 2 and 3 in figure 1(f)) and amplitude ΔI (curves 1′, 2 and 3 in figure 1(g)) versus voltage U_1 applied to the sample placed in a constant magnetic field. When $\boldsymbol{H} \uparrow\uparrow \boldsymbol{E}$, the decrease of the oscillation frequency occurs at lower values of U than when $H = 0$, i.e. $f_H(U) < f(U)$

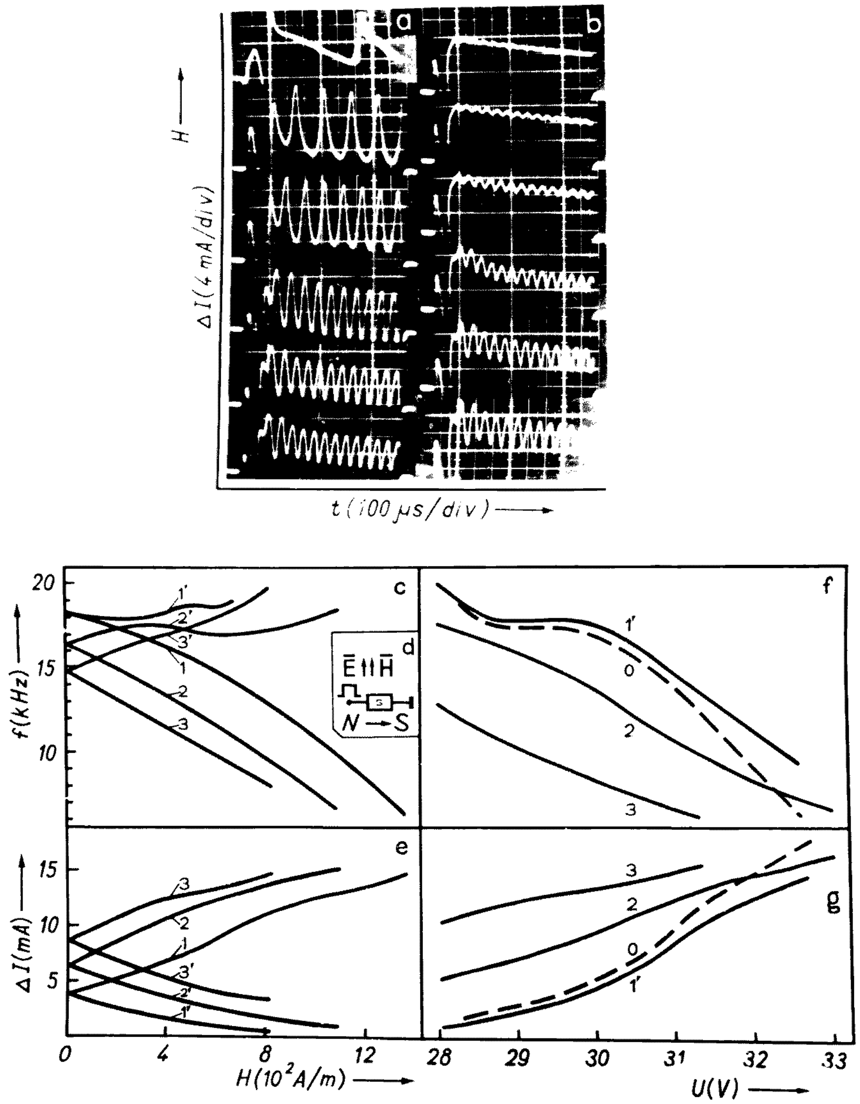

Figure 1. Change in the current oscillation frequency and amplitude of mode I in the external circuit of InSb samples with magnetic field: (a) oscillograms at $\boldsymbol{H} \uparrow\uparrow \boldsymbol{E}$, ($U_2 = 30.3$ V); (b) oscillograms at $\boldsymbol{H} \downarrow\uparrow \boldsymbol{E}$, ($U_2 = 30.3$ V); (d) orientation of a sample relative to the direction of the electric and magnetic field; (c), (e) magnetic field dependence of the oscillation frequency and the amplitude in constant electric voltage: 1, $U_1 = 29.5$ V; 2, $U_2 = 30.3$ V and 3, $U_3 = 30.8$ V at $\boldsymbol{H} \uparrow\uparrow \boldsymbol{E}$; 1′, 2′ and 3′ at $\boldsymbol{H} \downarrow\uparrow \boldsymbol{E}$; (f), (g) electric voltage dependence of the oscillation frequency and the amplitude in constant magnetic field: 0. $H = 0$; 1′. $H = 136$ A m^{-1} ($\boldsymbol{H} \downarrow\uparrow \boldsymbol{E}$); 2. $H = 544$ A m^{-1} ($\boldsymbol{H} \uparrow\uparrow \boldsymbol{E}$); 3. $H = 1088$ A m^{-1} ($\boldsymbol{H} \uparrow\uparrow \boldsymbol{E}$).

(curves 0, 2 and 3 in figure 1(f)). When $\boldsymbol{H} \downarrow\uparrow \boldsymbol{E}$, we have $f_H(U) > f(U)$ (curves 0 and 1′ in figure 1(f)). The dependences of the oscillation amplitude versus voltage in constant magnetic field are arranged in reverse order, i.e. $\Delta I_H(U) > \Delta I(U)$ when $\boldsymbol{H} \uparrow\uparrow \boldsymbol{E}$ (curves 0, 2 and 3 in figure 1(g)) and $\Delta I_H(U) < \Delta I(U)$ when $\boldsymbol{H} \downarrow\uparrow \boldsymbol{E}$ (curves 0 and 1′ in figure 1(g)).

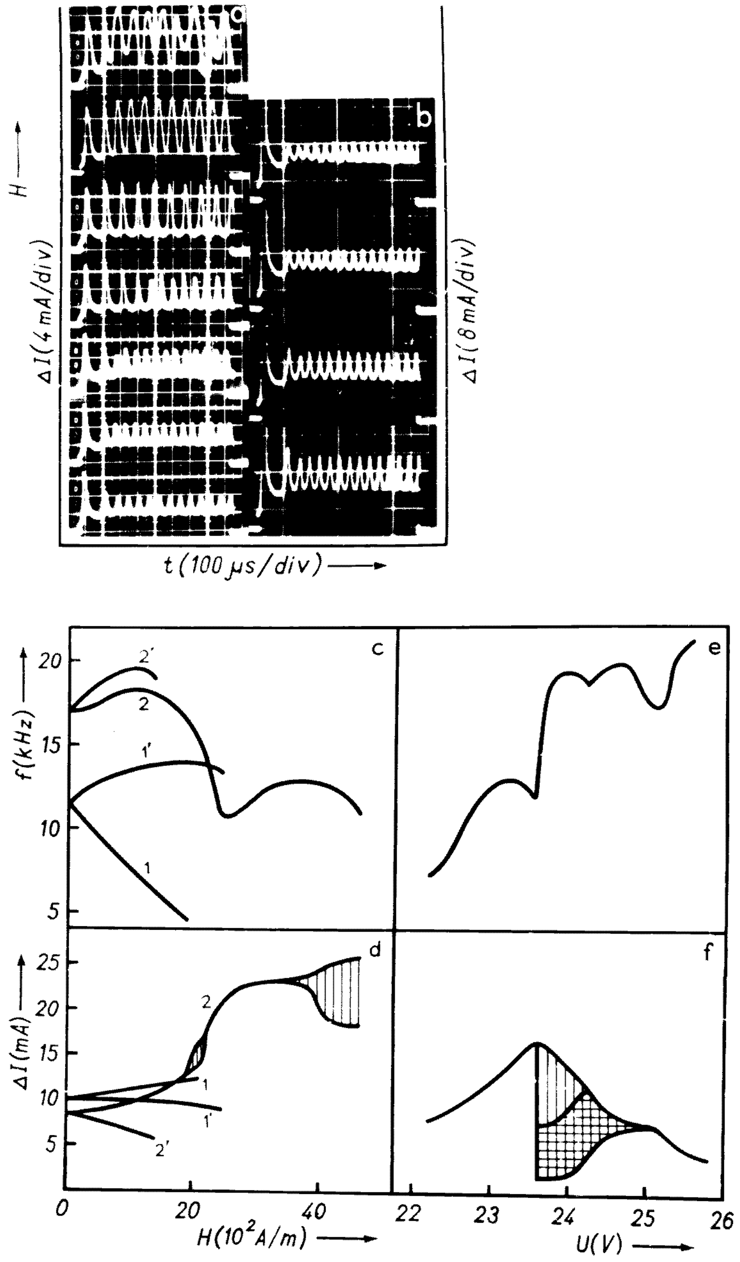

Figure 2. Change in the current oscillation frequency and amplitude of mode II in the external circuit of InSb samples with magnetic field: (a) oscillograms at $\boldsymbol{H} \uparrow\uparrow \boldsymbol{E}$, $U_2 = 25.1$ V; (b) oscillograms at $H \downarrow\uparrow \boldsymbol{E}$, $U_2 = 25.1$ V; (c), (d) magnetic field dependence of the oscillation frequency and amplitude in constant electric voltage: 1, $U_1 = 22.7$ V and 2, $U_2 = 25.1$ V at $\boldsymbol{H} \uparrow\uparrow \boldsymbol{E}$; 1′ and 2′ at $\boldsymbol{H} \uparrow\downarrow \boldsymbol{E}$; (e), (f) voltage dependence of the oscillation frequency and amplitude at $H = 0$.

Figure 2 shows the effect of magnetic field on frequency and amplitude of the current oscillation mode II [13]. Figure 2(e), (f) shows how that mode varies with applied voltage.

In a given case, it undergoes not only a period doubling bifurcation but also a period tripling bifurcation as electric field increases. The hatched lines mark the voltage regions where doubling and tripling of the cycle take place while region boundaries point out the current amplitude of the cycles. Oscillograms in figure 2(a), (b) illustrate the change of the oscillation frequency and amplitude with the magnetic field increase from 0 to 4800 A m^{-1} when $\boldsymbol{H} \uparrow\uparrow \boldsymbol{E}$ (figure 2(a)) and when $\boldsymbol{H} \downarrow\uparrow \boldsymbol{E}$ (figure 2(b)). Corresponding graphs demonstrate that when $\boldsymbol{H} \uparrow\uparrow \boldsymbol{E}$ the frequency decreases with the magnetic field increase (figure 2(c), where the curves 1 and 2 correspond to different values of initial voltage $U_1 < U_2$). With this, at the voltage U_1, current oscillations take place when the magnetic field increases from 0 to 2150 A m^{-1}. At opposite orientation of the magnetic and the electric field $\boldsymbol{H} \downarrow\uparrow \boldsymbol{E}$, the oscillation frequency increases but it tends to decrease at higher magnetic field strengths.

Figure 2(d) shows the magnetic field dependences of oscillation amplitudes. At the voltage U_1 and $\boldsymbol{H} \uparrow\uparrow \boldsymbol{E}$, the oscillation amplitude increases gradually as the magnetic field increases (curve 1 in figure 2(d)). At $U_2 > U_1$ and $\boldsymbol{H} \uparrow\uparrow \boldsymbol{E}$, the oscillation amplitude increases noticeably as the magnetic field increases (curve 2 in figure 2(d)). Finally, when the magnetic field changes from 1900 to 2200 A m^{-1}, the mode undergoes a period doubling bifurcation. With further magnetic field increase, regular oscillations are generated. The amplitude of these oscillations increases sublinearly and when $H > 3300$ A m^{-1} another period doubling bifurcation takes place. At U_1 and U_2, when $\boldsymbol{H} \downarrow\uparrow \boldsymbol{E}$, the amplitudes of the modes decrease almost linearly with the magnetic field increases.

4. Discussion

In spite of the fact that changes of amplitude and frequency of oscillations of a current when changing the magnetic field at $\boldsymbol{H} \uparrow\uparrow \boldsymbol{E}$ are similar to the behaviour of amplitude and frequency of oscillations of a current with increase of electrical field, it is impossible to decide whether the given situation is caused by an increase of resistance of a sample in a magnetic field, or by increase of an electrical field in a sample. The used low longitudinal magnetic field will not lead to any increase of resistance, since in semiconductors with a spherical isoenergetic surface, as InSb is, longitudinal magnetoresistance is absent [15]. The odd behaviour of amplitude and frequency of oscillations of a current in InSb in a longitudinal magnetic field at $\boldsymbol{H} \uparrow\uparrow \boldsymbol{E}$ and $\boldsymbol{H} \downarrow\uparrow \boldsymbol{E}$ is caused, most likely, by a decisive contribution of thermomagnetic effects. The ASs either in the form of longitudinal current filaments, or layers with low carrier density directed transversal to the current lines, give rise to localized overheated regions with a sharp gradient $\nabla T = (T_{AS} - T)/(\mathcal{L}/2)$, where T_{AS} is the temperature in the centre of the AS, T is the temperature at the AS edges; $T_{AS} \approx 2T$ [16], $l < \mathcal{L} < (Ll)^{1/2}/2$ is the width of the AS [6], L is the diffusion length of the carriers and l is the cooling length of the carriers.

Thus, $\nabla T = 2T/\mathcal{L} = (2T/l)/[4T/(Ll)^{1/2}]$. For InSb, $T \geqslant 150$ K [13], $L \approx 3 \times 10^{-3}$ cm and $l \approx 9 \times 10^{-4}$ cm [17, 18].

$\nabla T = (3.3 \times 10^5$–$4 \times 10^5)$ K cm^{-1}. In a longitudinal magnetic field, the existence of a transverse temperature gradient ∇T of a current filament (AS) due to the Nernst–Ettinghausen effect results in the appearance of a transverse voltage. The field of the transverse Nernst–Ettinghausen effect is an odd function of H, i.e. the sign of the transverse voltage depends on the magnetic field direction, $E_\perp(H) = -E_\perp(-H)$ [19]. The equation for the transverse voltage in the case of a low magnetic field is $E_\perp = a_r(1/2 - r)(k/e)(\mu_e H/c)\nabla T$ [19], where $r = 1$ is the scattering factor at which $a_r = 1.1$; μ_e is the electron mobility, $\mu_e = b\mu_p$, μ_p is the hole mobility,

$b = \mu_e/\mu_p$, $b \sim 6.3T^{1/2}$, $b(T = 250\ \text{K}) \approx 100$ [20], $b = 100(T/250\ \text{K})^{1/2}$, $\mu_e(T) = \mu_e(77\ \text{K})(T/77\ \text{K})^{-1.7} = 100(T/250\ \text{K})^{1/2}(T/77\ \text{K})^{-1.7}$, $\mu_p(77\ \text{K}) = 4000\ \text{cm}^2\ \text{V}^{-1}\ \text{s}^{-1}$, $T = 300$ K, $H = 8 \times 10^3\ \text{A m}^{-1}$ gives $E_\perp = -(0.35\text{–}0.43)$ V. At this voltage, the AS has moved into or out of the current filament. In the first case, the AS enters a denser and hotter EHP; in the second case it enters an EHP of lower density and temperature. In both cases the values of μ_e, μ_p, T_e, T_p will change. This results in a change of the AS phase velocity V_{ph} [7]. Calculations of the phase velocity were made [7] by the equation

$$V_{ph} = \frac{2\alpha\mu_e\mu_p(\mu_e+\mu_p)^{-1}}{\alpha^2(T_e - T_0)(T_p - T_0) - \alpha(\mu_e+\mu_p)^{-1}(\mu_e-\mu_p)(T_e-T_p)T_0} \times \frac{ET_0(T_p - T_e)}{-[(1-s)T_e + sT_0][(1-s)T_p + sT_0]} \qquad (1)$$

where T_e is electron temperature, T_p is hole temperature, T_0 is lattice temperature, E is electric field applied to the sample. For InSb $\alpha = -1/2$, $s = 1$. As $m_p^* \gg m_e^*$, then $T_p = T_0 \approx 80$ K [6]. Then equation (1) at $E = 10\ \text{V cm}^{-1}$ gives

$$V_{ph} = \frac{4.44 \times 10^4 (T_e/77\ \text{K})^{-1.7}[100(T_e/250\ \text{K})^{1/2}+1]^{-1}(T_e - 80\ \text{K})}{[100(T_e/250\ \text{K})^{1/2}+1]^{-1}[100(T_e/250\ \text{K})^{1/2}-1](T_e - 80\ \text{K}) - 160\ \text{K}}\ \text{m s}^{-1}. \qquad (2)$$

A moving AS is formed in a cool region of the EHP [13]. Let the temperature in this region be $T_e^0 = 130$ K. The calculation of (2) within the temperature range of the EHP 110 K $< T_e <$ 150 K shows (figure 3) that the AS velocity increases in a hot region and decreases in a cool region. Correspondingly, the oscillation frequency increases in the first case and decreases in the second case.

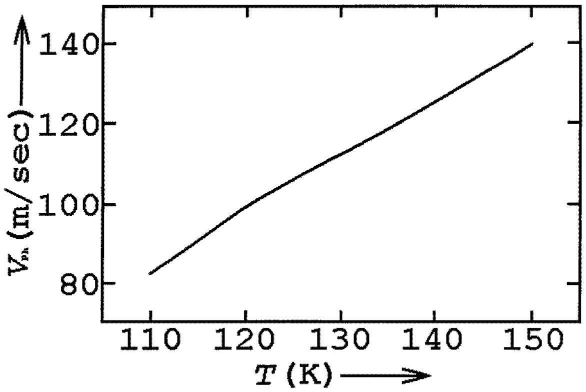

Figure 3. The AS velocity versus the EHP temperature in InSb.

In a hotter and denser region of the EHP the carrier density drop in an AS will decrease, i.e. the resistance will decrease as well as the electric field in the centre of the AS. This results in a decrease of the current jump in the external circuit of the sample when a moving hot AS is decomposed.

In relatively cool and less dense regions of the EHP the carrier density drop in an AS will increase, therefore the resistance will increase as well as the electric field in the centre of the AS. This results in an increase of the current jump in the external circuit of the sample while the moving hot AS is decomposed. It can explain why the current oscillation amplitude decreases when the AS moves to a hotter and denser region of the EHP and increases when the AS moves to a colder and less dense region.

5. Conclusions

In conclusion, it is shown experimentally that a longitudinal magnetic field of relatively small value (up to 10^4 A m^{-1}) causes the noticeable change in the velocity of AS excited by strong heating in external fields in InSb samples. As this takes place, the frequency of current oscillations in the external circuit of the sample decreases while the oscillation amplitude increases as the magnetic field parallel to the electric field ($\boldsymbol{H} \uparrow\uparrow \boldsymbol{E}$) increases. At reverse direction of the magnetic field ($\boldsymbol{H} \downarrow\uparrow \boldsymbol{E}$), the oscillation frequency increases while the oscillation amplitude decreases as the magnetic field increases.

Acknowledgment

The authors wish to thank Professor V V Osipov for his kind attention to this work, useful comments and additions made during discussion.

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