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Acoustoelectric effect in a transverse magnetic field in a piezoelectric semiconductor: evidence for universal behaviour and nonlinear effects

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Abstract. A new analysis of the previously published data on the acoustoelectric effect in n-InSb along a piezoelectric orientation in a transverse magnetic field is presented. It is observed that the data follow a simple equation relating the current density j through the samples to the magnetic field B : $j \approx 1/(1 + (\mu B)^2)$. This equation originates from the Steele modification of the Hutson–White model for piezoelectric semiconductors in a transverse magnetic field. Good agreement with this equation is also observed for recent truly nonlinear acoustoelectric measurements. It is suggested that this law appears to describe a universal behaviour of the magneto acoustoelectric effect and that the nonlinearity effect should be taken into account.

1. Introduction

1.1. Short review of acoustoelectric effects: acoustic amplification and current oscillations

The observation of acoustic-wave amplification by Hutson *et al* [1] in 1961 led to the possibility of producing an acoustic-wave amplifier using piezoelectrically active semiconductors. In the amplification effect, mobile charge carriers drifting faster than the speed of sound can couple to the acoustic waves of the lattice because the piezoelectric and deformation potentials generate internal electric fields. Under the right conditions, sound attenuation can become negative, hence a net amplification or gain of the acoustic wave can occur. For several years, investigations of the acoustic-wave amplification effect were confined mostly to CdS because of its superior acoustic and electronic properties. These results have been largely discussed by McFee [2] and reviewed also by Meyer and Jörgensen [3]. However, it was observed that, after sufficient amplification (or gain), the acoustoelectric current and domain became an even larger portion of the acoustoelectric response to the sound wave in the presence of the drift electric field. This regime of acoustic amplification appeared to occur also when the current saturation effect was observed in the I–V characteristics of the sample. The presence of these domains contributed largely to the loss of interest in the acoustic amplification effect since these domains were understood to be the main contributors to the large electrical noise present in acoustoelectric devices, making them not very useful. The current saturation (corresponding to maximum acoustic gain) was also largely explained by the model of acoustic attenuation in a piezoelectric semiconductor in the regime where the acoustoelectric interaction is dominated by the piezoelectric potential for

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moderate frequencies. This saturation was understood as originating from the acoustoelectric current produced by the free carriers reacting to the growing sound flux in the sample. The most successful and widely used model is the Hutson–White [4] model describing sound attenuation in a piezoelectric semiconductor. It was later extended by Hutson [5] to incorporate the effect of an applied electric field to describe the sound amplification effect. This macroscopic model describes the interaction of collision-dominated electrons with acoustic waves of long wavelength. Tien [6] produced a nonlinear theory to explain with more confidence gain saturation in the limit of a large wave amplitude. It was then suggested that the high-frequency current oscillations generated by the material itself may be related to the current and gain saturation.

Similar acoustic-wave amplification effects have been observed in II–V semiconductors but in the presence of a transverse magnetic field which could affect significantly the electronic component of the acoustoelectric effect. Acoustoelectric current oscillations were first investigated by Bray *et al* [7]. Kikuchi *et al* [8] and Kino and Route [9] observed that the current threshold for current oscillations in n-InSb at 77 K along a piezoelectric direction (namely the [110] direction for n-InSb) decreased with increasing magnetic field and became saturated above 0.3 T. Route and Kino [10] and Prieur [11] showed that the saturation of the acoustic gain to a maximum value and the reduction in the current threshold for oscillations with increasing magnetic field were observed in acoustic-wave amplification experiments in n-InSb. This reduction in transverse magnetic field was explained by Route and Kino by an extended Hutson–White model. Their model was derived from the Hutson–White model as modified by Steele [12]. He suggested a simple method to include the magnetic-field-induced reduction in the RF mobility in the macroscopic Hutson–White model in the presence of an externally applied electric field. More specifically, Route and Kino explained the presence of current oscillations and their magnetic field dependence by invoking a threshold gain factor in the acoustic amplification in order to predict the generation of oscillations. Abe and Mikoshiba [13] suggested also that the observation of current oscillations strongly implied that the current instability should be closely related to the amplification of acoustic waves. Similarly they used an extended Hutson–White model to incorporate the effect of the transverse magnetic field. In their model the DC electric field is seen to provide a shift in the phase of the AC electric field to maximize the energy transfer between the carriers and the acoustic wave. They reproduced semiqualitatively the reduced threshold for maximum gain and the magnetic field dependence of the current threshold for current oscillations if they defined a suitable minimum amplification factor or gain for the generation of oscillations. Flewing and Rowe [14] also developed a model explaining most of these features on the acoustic amplification and current oscillations.

However, all these theories described complex models to explain both properties. Furthermore the description of the presence of current oscillations lacked a simple explanation or physical equation that would relate more directly to the acoustic amplification theories. All the models in a finite magnetic field neglected the inclusion of nonlinear effects while the maximum gain and current oscillations were believed to be effects that belong to strong-electric-field conditions and hence a nonlinear regime. The main results of these experiments in a magnetic field can be summarized in the following way: the acoustic gain (or amplification) saturates at a lower value of electric field in a finite low magnetic field while current oscillations are observed whenever substantial gain is achieved in the system for an electric field applied along a piezoelectric direction. No simple link was made between acoustic gain and current oscillations except through extensive numerical simulations based on linear acoustic amplification theories.

1.2. Recent nonlinear acoustoelectric voltage studies

More recently Skorupka *et al* [15] have shown that these acoustoelectric RF current oscillations in n-InSb in the presence of a transverse magnetic field are nonlinear voltages that can develop in a truly deterministic chaotic regime. In these experiments a nonlinear dependence on the DC current or electric field through the sample along a piezoelectric direction is implied. The nonlinearity appears when a sufficiently large electric field provides an electron drift velocity v_D larger than the sound velocity v_s. The chaotic properties of these oscillations have been studied by showing that the attractor dimension exhibits chaotic properties. We have shown in our own work [16] that these oscillations have a complex nonlinear and chaotic regime in agreement with the results of Skorupka *et al*. We also showed clearly that the current acoustoelectric chaotic oscillations found in n-InSb were related to the piezoelectric effect, a result which had always been assumed in all previous studies. Furthermore for the first time it was shown that the linear acoustic amplification theory based on the Hutson–White model and modified to include the magnetic-field-limited RF mobility led to a simple interpretation of the data. Our simple model was successful in explaining the relationship between the magnetic field and the threshold current density j necessary to generate both nonlinear and chaotic oscillations.

In this paper it is shown that this simple relation between threshold current density and magnetic field can explain with reasonably good agreement both the data discussed above relating to sound amplification and the current oscillations in any given regime (whether they have been stipulated as nonlinear or not in the original studies). This comparison gives for the first time a unified view of the sound amplification, the current oscillations and the presence of nonlinear effects as measured by more modern methods. This simple interpretation confirmed indirectly the prediction of Steele [12]. He suggested that the magnetic field effectively reduced the electron drift velocity needed to maximize acoustic gain in a high-mobility semiconductor such as InSb.

2. Linear theory of acoustic wave gain in piezoelectric semiconductors in a transverse magnetic field

The linear theory for acoustic amplification in piezoelectric semiconductors gives for the acoustic wave gain α, as modified by Steele [12] to include transverse magnetic fields effects, the following expression [3, 12]:

$$\alpha = \frac{K^2\omega_c}{2V_s}\frac{\gamma(1+\mu^2B^2)}{\gamma^2(1+\mu^2B^2)^2+(\omega_c/\omega+\omega/\omega_D)^2} \tag{1}$$

where

$$\gamma = \frac{j}{env_s} - 1$$

K is the electromechanical coupling constant, ω is the acoustic wave frequency, $\omega_c = \sigma/\varepsilon$ is the dielectric relaxation frequency, $\omega_D = v_s^2/D$ is the diffusion frequency, v_s is the sound velocity, and σ, ε, D, n, j and μ are the conductivity, dielectric constant, diffusion coefficient, charge density, current density and mobility of electrons, all of these last quantities in zero magnetic field. From the above expression it is predicted that no amplification or gain as well as no nonlinear or chaotic behaviour should be observed (meaning a negative gain α) if the current density j is lower than $j_s = nev_s$ or if the electron drift velocity v_D is lower than the sound velocity ($v_D < v_s$). This is consistent with the vast amount of data on amplification and current oscillations supporting the existence of this threshold. However, the recent work of Skorupka *et al* and our own work have shown that truly nonlinear voltage oscillations also exhibit the same threshold to nonlinearity.

Aronzon and Guillon [16] showed that the measurements of the nonlinear voltage oscillations are performed at a relatively low frequency which is much smaller than the frequency at which maximum amplification (or gain as given by (1)) occurred. Therefore equation (1) should reduce to

$$\alpha = \frac{K^2\omega^2}{2V_s\omega_c}\gamma(1+\mu^2B^2). \tag{2}$$

They also showed that their nonlinear data agreed with the assumption that the gain (or α as given by (2)) should be constant because the threshold current data for the generation of nonlinear oscillations fitted very well the following expression derived from (2) and (1):

$$j - nev_s \approx \frac{nev_s}{1+(\mu B)^2}. \tag{3}$$

This result assumed also that a fixed frequency range apply to the data. This equation describes much better the connection between magnetic field and acoustic amplification theory since it emphasizes the reduced RF mobility effect in the expression $1/(1+(\mu B)^2)$ and provides more physical insight into this nonlinear acoustoelectric phenomena.

3. Results and discussion

Equation (3) relating injected current density to the applied magnetic field was used to describe various data in the literature showing direct acoustic amplification, the threshold of current oscillations and recent nonlinear acoustoelectric voltages in order to demonstrate the universal behaviour behind this equation. The selected data described experiments with n-InSb near 77 K except for the data of Skorupka *et al* at 148 K describing important nonlinear features which was only recently available.

Table 1 gives the relevant information for the data analysis. The data of Demko *et al* [17] describes the results of the current oscillations threshold for the so-called mode II [8] type obtained in a pulsed electric field. The selected results of Route and Kino [10] described similarly these current oscillations for mode II. Kikuchi *et al* [8] obtained very similar results on this mode II type of oscillations; so it will not be repeated here for clarity. The results of Prieur [11] were selected as representative of experiments that described the necessary current injected along [111] to obtain sound amplification. As seen in the table 1, two types of data belonging to the work of Prieur were selected: the current needed to obtain gain below the maximum gain and the current at which maximum amplification or gain is observed as a function of electric field (or injected current). The data labelled nonlinear oscillations described the results of truly nonlinear measurements showing the current threshold to nonlinear behaviour for Aronzon and Guillon [16] and the current threshold to chaos for Skorupka *et al* [15].

To show the universal behaviour behind equation (3) the current density j was computed and plotted as j versus $1/(1+(\mu B)^2)$ where μ is the zero-magnetic-field mobility given by the authors. Figure 1 illustrates the results of this analysis. Since the data were found to extend over a large range of j- and μB-values the current density j data of Demko *et al* were divided by 100, and the maximum gain data of Prieur were divided by 10. Furthermore, the data were divided into two graphs (figures 1(a) and 1(b)) for clarity in order that we could compare them more easily. Figures 1(a) and 1(b) illustrate the main finding of this paper. It is observed that the current density j is linear in $1/(1+(\mu B)^2)$ for all the data selected in the present work. Some scatter can be seen in curve e relating to the

Table 1. List of experimental data chosen to show the universal behaviour of equation (3) used to describe the sound amplification, current threshold for oscillations and nonlinear voltage oscillations in n-InSb in a transverse magnetic field.

Experiment	Mode	n (10^{14} cm^{-3})	μ (m^2 V^{-1} s^{-1})	T (K)
Current oscillations threshold	[110][a]	7	36	90
Amplification (below maximum gain)	[111][b]	2.3	50	77
Amplification (at maximum gain)	[111][b]	2.3	50	77
Nonlinear voltage oscillations	[111][c]	0.9	4.8	77
Current oscillations threshold	[110][d]	1.4	51	77
Nonlinear voltage oscillations	[110][e]	3	10	148

[a] [17].
[b] [11].
[c] [16].
[d] [10].
[e] [15].

work of Skorupka *et al*, but this scatter is mostly due to the original data at 148 K which did not show experimental points but only a smoothed continuous curve of poor quality (no details were given about experimental errors). Our own results [16] shown in figure 1(b) appeared to be outside the range of the other data but this is mostly a consequence of the low mobility of our sample and the low magnetic field range (0.1–0.4 T) where the nonlinear threshold results were obtained; hence the factor $1/(1+(\mu B)^2)$ is larger compared to other data. Moreover our data (curve c) appeared to show distortion of the linear dependence illustrated in figure 1. In the original data plotted as $j - j_s$ [16], it was shown more clearly that the data exhibited clearly some scatters due to the experimental method of collecting data and the noise present in the experiment. Finally the straight line depicted in figure 1(b) as curve c was computed using all the points despite the fact that the original data [16] showed with more confidence that the last point near $1/(1+(\mu B)^2) = 0.35$ appeared outside the straight-line dependence. However, since this feature was only observed in one point at a low magnetic field and we could not exclude an increased scatter or a serious error for this unique point, nothing can be concluded with absolute certainty. It should be mentioned that, if this feature were reproduced in many more data at low magnetic fields for a low-mobility sample, then this behaviour would strongly suggest that the universal behaviour exhibited in the data presented here would only be valid in a specific range of magnetic field and mobility conditions. More experiments are needed to clarify this aspect of the present work but this behaviour does not change the general conclusion of this work. Figure 1 also shows that the data exhibit some variation in the slope of this linear relationship according to equation (3). This equation predicts that the slope has some physical meaning and should be proportional to the product of carrier density n and sound velocity v_s, two quantities which are known independently as seen in table 1. Figure 2 shows the results of plotting the slope obtained by linear least-squares fitting of all curves in figure 1. Except for the data of Skorupka *et al* at 148 K, the other data do show a general trend of increasing slope with larger values of nv_s. The reasonable agreement with this expected trend is good since extensive transport measurements to obtain precise values of n and μ for the sample measured were made only in the work of Aronzon *et al* to our knowledge. Furthermore it should be noted that a variation of as much as 15% was found in the values of μ quoted in the papers relative to some experiments by Kino and Route. The good agreement for the linear relationship found in figure 1 and the increasing trend found in figure 2 should then be considered reasonable in view of the uncertainties in the value of n, μ and v_s since nominal values (see table 1) were used assuming a pure sound mode along the [111] and [110] direction.

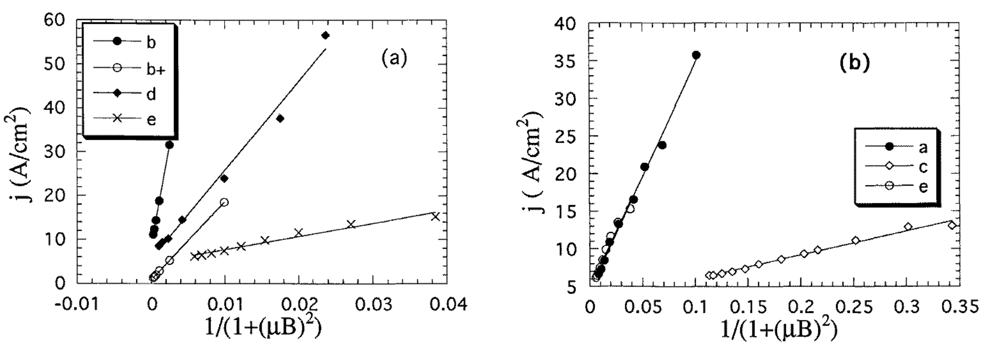

Figure 1. Data analysis of current density j versus $1/(1+(\mu B)^2)$ corresponding to equation (3) for data taken from the literature: (a) data of Prieur [11] (curves b and b^+ for maximum gain data), Route and Kino [10] (curve d) and Skorupka *et al* [15] (curve e); (b) data of Aronzon and Guillon [16] (curve c) Demko *et al* [17] (curve a) and Skorupka *et al* [15] (curve e) for ease of comparison. The full lines are linear least-squares fits according to equation (3). For each curve, only a limited number of points is shown for clarity.

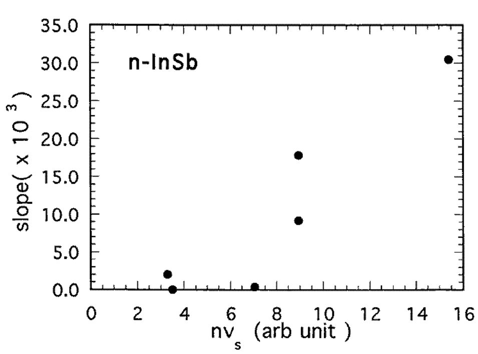

Figure 2. Relationship between the slope obtained by linear least-squares fitting of all curves in figure 1 as a function of nv_s. This figure demonstrates the universal behaviour of the acoustoelectric effect according to equation (3).

Despite the fact that there have been many reviews of data concerning the acoustoelectric effect in III–V semiconductors in a transverse magnetic field [2, 3, 14], to our knowledge this is the first time that a comparison has been made between various types of experiment on the acoustoelectric effect in a transverse magnetic field with a simple and unique relation such as equation (3). The present results shown in figures 1 and 2 demonstrate that the linear relationship between the current density j and the well known factor $1/(1+(\mu B)^2)$ in transport measurements appears to be a universal behaviour describing a magneto-acoustoelectric effect in increasing the electric field at least at 77 K for n-InSb, a material which has been extensively studied.

This important result confirmed that current oscillations, amplification experiments and nonlinear acoustoelectric signals are various signatures of the same acoustoelectric effect. It also confirms the suggestion of Abe and Mikoshiba that current oscillations and acoustic amplification are related; however, the present work definitely puts a new broader perspective on our understanding of the acoustoelectric effect. Furthermore the result on the slope and the linear relationship in figure 1 would suggest that n, v_s and μ are definitely key parameters that control the acoustoelectric effect in a magnetic field, a result which has already been suggested from the basic equations of electrodynamic and elasticity, leading to the linear theory of Hutson and White. The present work would also predict that all the data obtained in an apparently moderate electric field might belong to a nonlinear regime of the acoustoelectric effect. Our previous nonlinear results and the present work suggest that, under acoustic amplification conditions such as those of Prieur, nonlinear AC signals should be present, hence providing other evidence for the importance of a nonlinear contribution to the acoustoelectric effect.

4. Conclusion

This work presented an analysis of some recent nonlinear acoustoelectric voltages and past current oscillations as well as acoustic amplification data relating to acoustoelectric experiments in n-InSb near 77 K. From a detailed analysis of the magnetic field dependence of the current density used in each experiment, it was found that a unique universal behaviour is apparent. This apparent behaviour confirms the extended Hutson–White model of treating III–V piezoelectric semiconductor in a transverse magnetic field according to a simple theory due to Steele [12]. The universal behaviour suggests strongly that the RF reduced mobility is an important factor in the magneto-acoustoelectric effect. Moreover our results strongly imply for the first time that nonlinearity is also a key element of the acoustoelectric phenomenon when external electric fields are applied in a piezoelectric direction. However, the present result may be valid only in the low-frequency regime and long-wavelength limit corresponding to the data analysed. Further work is needed to confirm the dependence of the slope in figure 1 on carrier density and sound velocity, hence providing further insight into the universality of the relationship between the current density, mobility and magnetic field for electrons interacting with sound waves in those piezoelectric semiconductors. Certainly this work should be extended to two-dimensional materials where the mobility and carrier density, two important physical parameters in this study, can easily be controlled and varied through persistent photoconductivity at low temperatures.

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