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Magnetophonon oscillation of the transverse magneto-Seebeck-coefficient in semiconductors

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Magnetophonon (MP) oscillations of the transverse magneto-Seebeck-coefficient $\alpha_\perp$ were investigated in HgTe, n-type InSb, and p-type Te, where the oscillations were clearly observed by using a second-derivative method. They were compared with those of the longitudinal coefficient, $\alpha_{\parallel}$, and with those of the transverse and longitudinal magnetoresistances, $\rho_\perp$ and $\rho_{\parallel}$. The estimated amplitudes of the oscillations were almost of the same order of, or larger than those of, $\alpha_{\parallel}$, $\rho_\perp$, or $\rho_{\parallel}$, in contrast to the early theoretical prediction that the MP oscillation of $\alpha_\perp$ should be very small. These facts may suggest the existence of a new origin of the MP oscillations of $\alpha_\perp$ which has not been taken into account in the previous theory. A possible mechanism is proposed and discussed, which is expected to be effective for semiconductors with polar coupling such as those investigated in this experiment.

I. INTRODUCTION

As with most scientific phenomena, the magnetophonon (MP) effect could have been predicted or observed many years before its actual discovery, as is stated in the review by Peterson.[1] It is instructive that the MP effect was not pointed out until the paper of Gurevich and Firsov (GF),[2] in spite of the fact that a transport theory general enough to include quantum-mechanical effects in magnetic fields had been worked out in the 1950s, particularly in the works of Kubo and others.[3–7] Shortly after the first theoretical papers of GF (Refs. 2 and 8) that predicted MP oscillations in the transverse magnetoresistance $\rho_\perp$, two groups independently reported observation of such oscillations in n-type InSb, in the longitudinal ($\rho_{\parallel}$) as well as the transverse ($\rho_\perp$) magnetoresistance, and also in the longitudinal magneto-Seebeck-coefficient $\alpha_{\parallel}$.[9–13] Theoretical analyses of the longitudinal properties were then published.[14,15]

Oscillations were also looked for but not seen in the transverse magneto-Seebeck-coefficient $\alpha_\perp$ in early experimental work.[1,11] The lack of oscillations in $\alpha_\perp$ has been considered to be in accordance with expectations, since in this case the Seebeck coefficient should be independent of carrier scattering as mentioned by Pavlov and Firsov.[15]

In 1977, however, Takita and Landwehr reported the MP oscillation of the transverse magneto-Seebeck-coefficient $\alpha_\perp$ in the zero-gap semiconductor HgTe.[16] The oscillation was observed over a wide temperature range by using a second-derivative method. The oscillation was reported as a new phenomenon, since it had not been predicted before its first observation. According to a subsequent experiment,[17] the oscillation amplitude of $\alpha_\perp$ was much larger than that of the longitudinal one ($\alpha_{\parallel}$) in HgTe. It has been found by the present authors that MP oscillations can be observed in n-type InSb and p-type Te; this work will be described in this paper. These facts are clearly in contrast to the early theoretical prediction that the MP oscillation of $\alpha_\perp$ should be very small.[15] This suggests the existence of a new origin for the MP oscillation of $\alpha_\perp$ which is common to many semiconductors and which was not taken into account in the early theory, although a possible interpretation peculiar to HgTe was proposed in the case of HgTe.[16]

On the other hand, it has been suggested[15] that the theoretical analysis of the MP oscillation of $\alpha_\perp$ may be rather complicated because it should include the Landau diamagnetism of the carriers in the nondissipative transport phenomena.[18,19] To our knowledge, however, a detailed theoretical discussion of the oscillation of $\alpha_\perp$ has been completely lacking up to now. Thus it is necessary to investigate more thoroughly the MP oscillation of $\alpha_\perp$ in detail for a wide variety of semiconductors.

In the present work, a detailed experimental investigation of the MP oscillation of $\alpha_\perp$ which can be observed in n-type InSb and p-type Te as well as in HgTe is performed by using a computerized measuring system of second-derivative curves. The oscillation has been investigated with emphasis on the relative magnitude of the oscillation amplitude and it is found to be comparable with that of $\alpha_{\parallel}$, as described below. These facts may suggest the existence of a new origin for the MP oscillation of $\alpha_\perp$ which has not been taken into account in the previous theory.

After a brief description of the experimental method in Sec. II, the observed MP oscillation of $\alpha_\perp$ is described for HgTe, n-type InSb, and p-type Te, respectively, in Sec. III. In this section the experimental results are shown with emphasis on the relative amplitudes and the extremal positions of the oscillation and compared with those for $\alpha_{\parallel}$ and $\rho_\perp$. In Sec. IV, a possible mechanism for the MP oscillation of $\alpha_\perp$ is discussed, which is expected to be effective for semiconductors with polar coupling as those investigated in this experiment.

II. EXPERIMENTAL METHOD

In the present experiment, the magnetic field dependence of the thermoelectric power in the transverse magnetic field (the transverse magneto-Seebeck-coefficient $\alpha_\perp$)

was measured up to about 9 T, together with the longitudinal magneto-Seebeck-coefficient $\alpha_{\parallel}$ and transverse ($\rho_{\perp}$) and longitudinal ($\rho_{\parallel}$) magnetoresistance, for HgTe, *n*-type InSb, and *p*-type Te. The MP oscillation of $\alpha_{\perp}$ observed in the second-derivative curves was investigated and compared with those of $\alpha_{\parallel}$, $\rho_{\perp}$, and $\rho_{\parallel}$. We have constructed a computerized system for measuring the magneto-Seebeck-coefficient and magnetoresistance with high accuracy; data processing such as differentiation and integration can be performed in accord with a desired prescription.

The thermoelectric power in a strong magnetic field was measured by a similar system used in the previous papers.[16,17,20] In order to measure the thermoelectric power with high accuracy, two thermocouples of Chromel-Au(Fe) were directly soldered to the samples with an In or In-Sn alloy. The temperature gradient along the samples was measured by these two thermocouples and the thermoelectric voltage of the sample relative to Au(Fe) was measured using the Au(Fe) wires of the thermocouples. The temperature gradient along the samples was kept constant during a measurement by using two small heaters which were automatically controlled independently through respective $SrTiO_3$ capacitance thermometers unaffected by the magnetic field. Care was taken to eliminate spurious thermoelectric effects, especially in the measurement of the MP oscillation of $\alpha_{\perp}$; it was checked by inverting the magnetic field direction so that the observed oscillation was not affected by the superposition of the Nernst-Etthingshausen effect on the thermoelectric voltage probes.

III. EXPERIMENTAL RESULTS

A. MP oscillation of $\alpha_{\perp}$ in HgTe

The first observation of the MP oscillation of $\alpha_{\perp}$ in HgTe was reported by Takita and Landwehr.[16] Recently, a more-detailed measurement of the effect and an analysis of the temperature dependence of the peak positions were reported by the present authors.[17] Figure 1 shows some typical examples of the second-derivative curves of $\alpha_{\perp}$ in almost intrinsic HgTe, where the electron concentration is almost the same as the hole concentration. Peaks are clearly observed at around 1.6, 2.9, and 6.0 T as is seen in the figure. As the sign of Seebeck coefficient is defined as negative for the electron, the peaks in Fig. 1 are either the maxima of the electronlike contribution or the minima of the holelike contribution to the Seebeck coefficient at the resonance magnetic field. The MP oscillation of $\alpha_{\parallel}$ was also observed for the same sample, which was similar to the result reported in Ref. 16.

In Fig. 2 the oscillation amplitude of the MP oscillation around 3 T is plotted against temperature for both $\alpha_{\perp}$ and $\alpha_{\parallel}$. The ordinate represents the oscillation amplitude normalized by the thermoelectric power in zero magnetic field. The amplitude was estimated from the second-derivative curves such as those in Fig. 1 by numerical integration after background subtraction. It is very remarkable that the oscillation amplitude of $\alpha_{\perp}$ is very large compared to that of $\alpha_{\parallel}$. It is one order of magnitude larger than that of $\alpha_{\parallel}$ around 50 K as seen in Fig. 2.

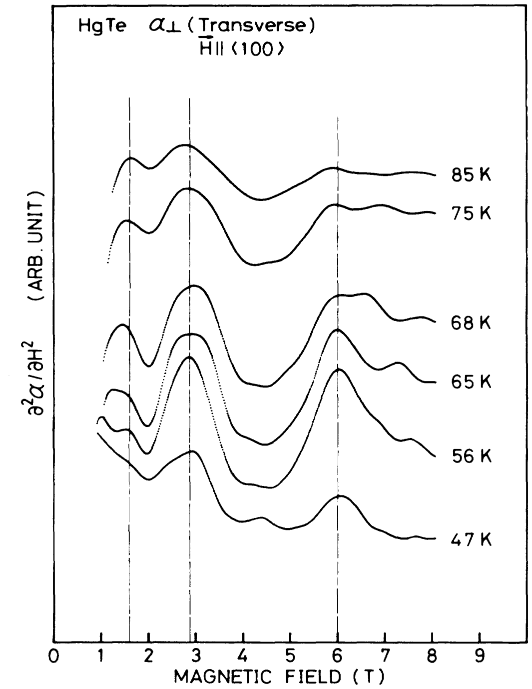

FIG. 1. Typical example of the second-derivative curves of transverse magneto-Seebeck-coefficient $\alpha_{\perp}$ of HgTe. Broken lines near the peak positions indicate the magnetic field values of 1.6, 2.9, and 6.0 T, respectively.

This experimental result seems to be quite anomalous because it has been predicted[15] that the MP oscillation of $\alpha_{\perp}$ should be much smaller than that of $\alpha_{\parallel}$. As is described in our previous paper[17], in the case of HgTe, the observed MP transition is assigned to be an interband

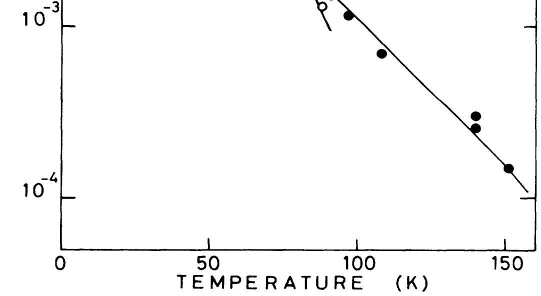

FIG. 2. Oscillation amplitudes of the MP oscillation extrema around 3 T of HgTe. Those in $\alpha_{\perp}$ and $\alpha_{\parallel}$, normalized by the thermoelectric power under zero field, are plotted against temperature, respectively.

transition. Therefore this transition may affect $\alpha_\perp$ through the two-carrier conduction mechanism or carrier recombination. Therefore, it is necessary to investigate further the MP effect of $\alpha_\perp$ in more common semiconductors, particularly in those with single-carrier conduction.

B. MP oscillation of $\alpha_\perp$ in n-type InSb

Figure 3 shows the second-derivative curves of the transverse magneto-Seebeck-coefficient $\alpha_\perp$ of n-type InSb with a carrier concentration of $n=1.3\times10^{14}$ cm^{-3}. Rather large minima were observed at around 3.3, 1.7, and 1.1 T in the temperature range from 140 K to above 250 K, as seen in Fig. 3. As the ordinate represents $\partial^2\alpha_\perp/\partial H^2$ and $\alpha_\perp$ is negative in this case, the minima in the figure mean those in the absolute value of the Seebeck coefficient. These curves were not affected substantially by the reversal of the magnetic field direction. Further, it should be pointed out that the MP oscillation in $\alpha_{\parallel}$ of this sample showed a phase-shifted maximum of its absolute value at about 4 T. These facts indicated that the observed oscillation in Fig. 3 is really the oscillation in the transverse Seebeck coefficient $\alpha_\perp$.

The magnetic fields of the minimum positions observed in Fig. 3 are plotted against the temperature in Fig. 4(a) and they are compared with the peak positions of the transverse magnetoresistance $\rho_\perp$ for $N=1$ and $N=2$. It is clearly seen that the extremum positions of $\alpha_\perp$ are in good agreement with that of $\rho_\perp$. It is well known[1] that

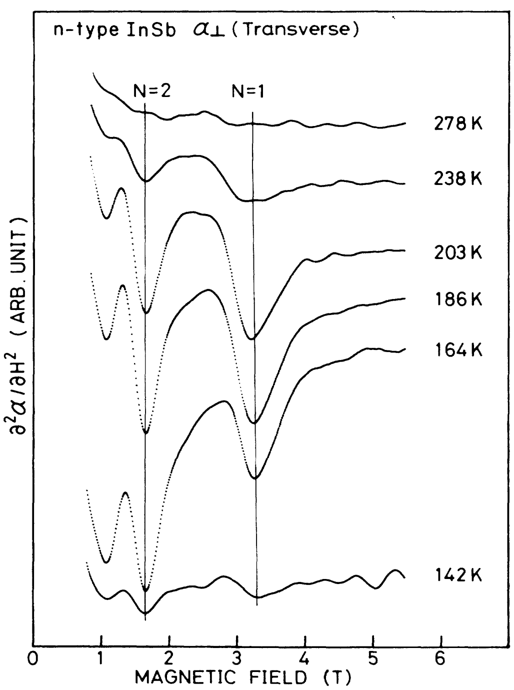

FIG. 3. Second-derivative curves of transverse magneto-Seebeck-coefficient $\alpha_\perp$ of n-type InSb at various temperatures. Observed minimum positions for $N=1$ and $N=2$ are indicated by the vertical lines which correspond to the GF resonance fields.

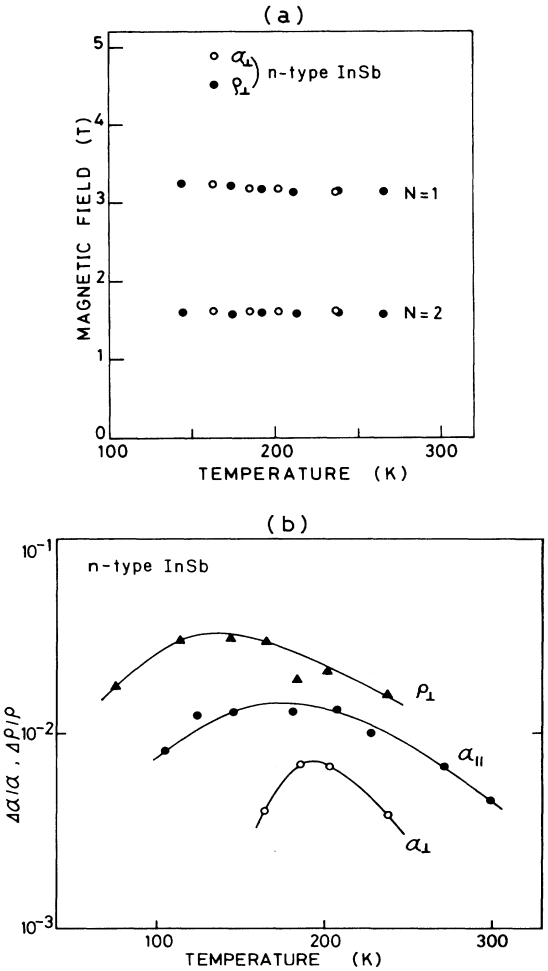

FIG. 4. (a) The magnetic fields of the minimum positions in the absolute value of $\alpha_\perp$ (open circles) and those of the peak positions in transverse magnetoresistance $\rho_\perp$ (solid circles) in n-type InSb are plotted against temperature. (b) Oscillation amplitudes of the MP oscillation extrema of $N=1$ of n-type InSb are plotted against temperature for $\alpha_\perp$, $\alpha_{\parallel}$, and $\rho_\perp$ respectively. The ordinate stands for the relative amplitude normalized by the background values of each coefficient at the magnetic field.

the peak positions of $\rho_\perp$ coincide with the magnetic field calculated by the resonance condition as follows:

$$E_{n,s}-E_{m,s}=\hbar\omega_0 \quad (s=\uparrow \text{ or } \downarrow)\ , \tag{1}$$

where $E_{n,s}$ ($E_{m,s}$) denotes the energy of the final (initial) state of the electron in Landau level n (m) with spin s, and $\hbar\omega_0$ is the long-wavelength LO phonon energy.

Figure 4(b) shows MP oscillation amplitudes for $\alpha_\perp$, $\alpha_{\parallel}$, and $\rho_\perp$, which were estimated from the second-derivative curves by the same method described in Sec. III A. The ordinate represents the relative amplitude of the $N=1$ extremum normalized by the background values of each coefficient at the magnetic field (around 3.3 T for $\alpha_\perp$ and $\rho_\perp$, and around 4T for $\alpha_{\parallel}$). As is seen, the amplitude of $\rho_\perp$ is several percent and that of $\alpha_{\parallel}$ is around 1% over a rather wide temperature range. Furthermore, the amplitude of $\alpha_\perp$ reaches a value of about 0.8% at around 200 K, which is comparable with that of $\alpha_{\parallel}$ and is a value unexpected from the early theoretical predictions.[15]

It is noted from Fig. 4(b) that the temperature range where the MP oscillation could be observed is narrower for $\alpha_\perp$ than for $\alpha_{\parallel}$ or $\rho_\perp$, and it corresponds to the temperature where the n-type—to—intrinsic transition beginning to occur for the sample. Thus the possibility of a relation between the MP oscillation of $\alpha_\perp$ and the two-carrier conduction cannot be ruled out completely even in n-type InSb. Therefore, we proceed to examine the MP oscillation of $\alpha_\perp$ in p-type Te, which has a wider energy gap and in which the MP oscillation is observed in a rather low-temperature range where only single-carrier conduction is manifested.

C. MP oscillation of $\alpha_\perp$ in p-type Te

1. **H**$\perp$**c** *case*

In p-type Te with a carrier concentration of $p = 2\times 10^{14}$ cm^{-3}, the MP oscillation of $\alpha_\perp$ in the magnetic field **H** perpendicular to the c axis was clearly observed in the second-derivative curves as is shown in Fig. 5. Since the ordinate stands for $-\partial^2\alpha_\perp/\partial H^2$ and $\alpha_\perp$ is positive in this case, the minima in Fig. 5 are those of the Seebeck coefficient. The minima were observed for the resonance fields of $N=4$, 5, 6, etc. as seen in the figure. The minimum positions of $\alpha_\perp$ were plotted against temperature and compared with the peak positions of $\rho_\perp$ in Fig. 6(a). The fields of both extrema were in agreement with each other, which indicates agreement with the resonance fields. The MP oscillation of magnetoresistance in p-type Te has been reported by Miura *et al.*[21]

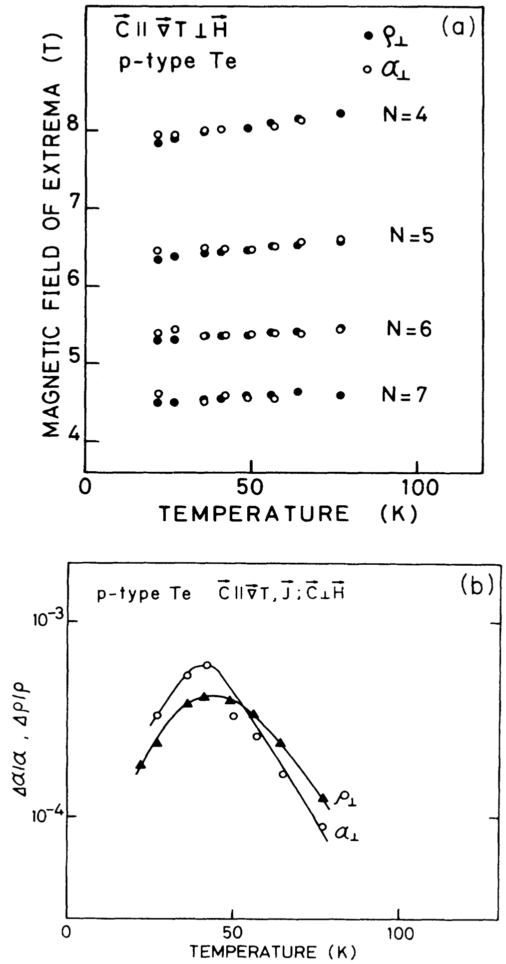

FIG. 6. (a) The magnetic fields of the minimum positions of $\alpha_\perp$ (open circles) and those of the peak positions in $\rho_\perp$ (solid circles) in p-type Te under **H**$\perp$**c** are plotted against temperature for $N=4$, 5, 6, and 7 extrema. (b) Oscillation amplitudes of the MP oscillation extrema of $N=5$ of p-type Te under **H**$\perp$**c** are plotted against temperature for $\alpha_\perp$ and $\rho_\perp$ respectively, shown similarly as in Fig. 4(b).

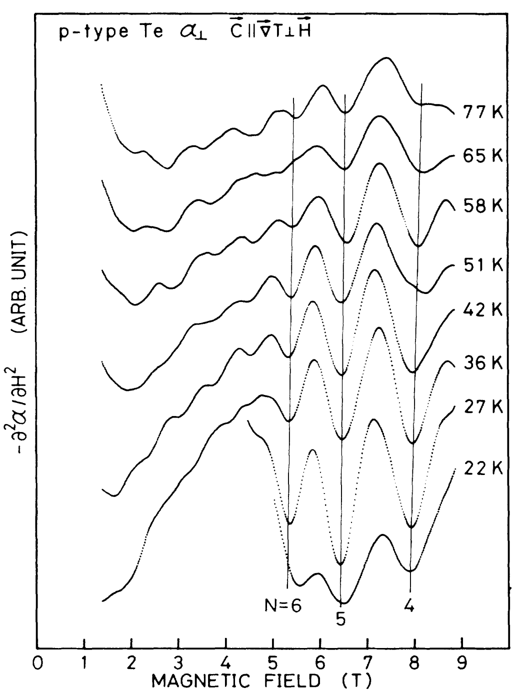

FIG. 5. Typical example of the second-derivative curves of transverse magneto-Seebeck-coefficient $\alpha_\perp$ of p-type Te under magnetic field **H**$\perp$**c**. Observed minimum positions are indicated by the vertical lines for $N=4$, 5, and 6.

In Fig 6(b) the MP oscillation amplitudes of $N=5$ minimum of $\alpha_\perp$ were plotted against temperature and compared with that of the transverse magnetoresistance $\rho_\perp$. They were estimated from the second-derivative curves by the same method described above and normalized by the value of the background at the peak positions. The amplitude of $\alpha_\perp$ was almost comparable with that of $\rho_\perp$ in the rather wide temperature range from 20 to 80 K as seen in Fig. 6(b).

2. **H**$\parallel$**c** *case*

The experiment was performed further for the case of **H**$\parallel$**c** of p-type Te with similar carrier concentration. The

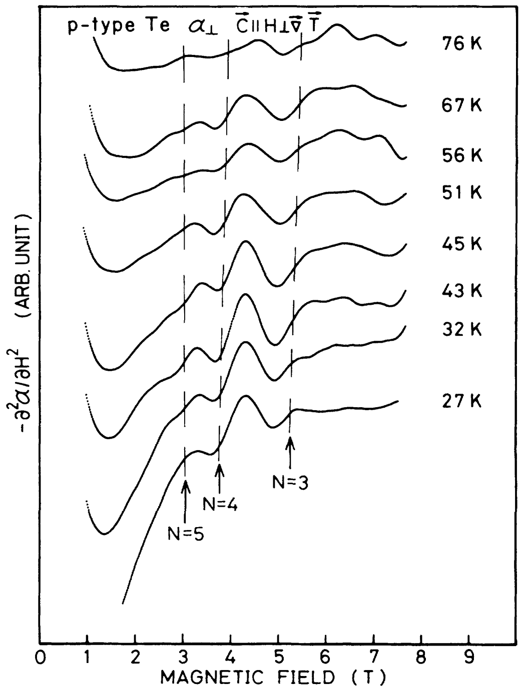

FIG. 7. The second derivative curves of transverse magneto-Seebeck-coefficient $\alpha_\perp$ of p-type Te under $\mathbf{H}\parallel\mathbf{c}$. The peak positions of $\rho_\perp$ for $N=3$, 4, 5 of the same sample are shown by broken lines for comparison.

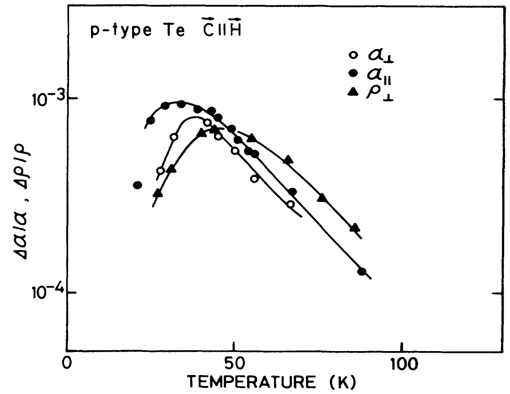

FIG. 8. Oscillation amplitudes of the MP oscillation extrema at around 5 T of p-type Te under $\mathbf{H}\parallel\mathbf{c}$ are plotted against temperature for $\alpha_\perp$, $\alpha_\parallel$, and $\rho_\perp$, shown similarly as in Fig. 4(b).

second-derivative curves of $\alpha_\perp$ are shown in Fig. 7. Some oscillation curves were also observed as seen in the figure but the extremum positions do not coincide with the peak positions of the MP oscillations of $\rho_\perp$ which are shown by broken lines. In Fig. 8 the oscillation amplitudes are plotted against temperature for the oscillation extrema around 5 T of $\alpha_\perp$, $\alpha_\parallel$ and $\rho_\perp$, respectively. Even in this case, they have comparable magnitude as is clear in Fig. 8.

We conclude this section by summarizing the experimental results of the present study of MP oscillation of $\alpha_\perp$ in Table I.

IV. DISCUSSION

The experimental results are summarized as follows.

(1) In HgTe, n-type InSb, and p-type Te, the amplitude of the MP oscillation of $\alpha_\perp$ was almost of the same order of, or larger than those of $\alpha_\parallel$, $\rho_\perp$ or $\rho_\parallel$, in contrast to the early theoretical prediction that it should be very small.

(2) Except for $\mathbf{H}\parallel\mathbf{c}$ case of p-type Te, the extremum positions of the oscillation coincide with the resonance fields determined by Eq. (1) without phase shift, which means they coincide with the peak positions of the MP oscillation of $\rho_\perp$ experimentally.

(3) The oscillation was observed even under the condition of single-carrier conduction as is clear in the case of p-type Te, although the possibility of the oscillation due to the coexistence of an electron and a hole could not be ruled out in the case of HgTe or n-type InSb.

(4) The temperature range where the phonon-drag effect could be observed in the thermoelectric power is below about 50 K for HgTe,[20] 60 K for n-type InSb,[22] and 40 K for p-type Te.[23] The phonon-drag effect disappears very rapidly with increasing temperature. Therefore it should

TABLE I. Experimental results of MP oscillation of $\alpha_\perp$. Question marks indicate results were unknown.

	HgTe	n-type InSb	p-type Te ($\mathbf{H}\perp\mathbf{c}$)	p-type Te ($\mathbf{H}\parallel\mathbf{c}$)
Extremum of $\lvert\alpha_\perp\rvert$ at the resonance field	maximum	minimum	minimum	?
Coincidence with the peak position of $\rho_\perp$	yes[a]	yes	yes	no
Oscillation amplitude	Fig. 2	Fig. 4(b)	Fig. 6(b)	Fig. 8
Kind of carrier	electron and hole	electron and minority hole	hole	hole
Resonance transition	interband[a]	intraband	intraband	?
$\omega_c\tau$ (at H)	$\sim$10 (at 3 T)	$\sim$20 (at 3 T)	$\sim$5 (at 6 T)	$\sim$3 (at 5 T)

[a]Reference 17.

be noted that the MP oscillations were observed even in the temperature range above the phonon-drag region, especially in the case of n-type InSb where they were observed far above the phonon-drag region.

(5) The magnitude of ω_c (where ω_c is the cyclotron frequency given by $\omega_c\tau=eH/m_e$ and τ is the scattering time of the carrier) is estimated to be more than 10 for HgTe and n-type InSb, and 3—5 for p-type Te, at the peak positions examined and in the temperature range concerned. Therefore the condition of high magnetic field is considered to be fulfilled for all the extrema of the oscillation examined in the present experiment.

In a magnetic field $\mathbf{H}$, the current density $\mathbf{J}$, electric field $\mathbf{E}$, and the temperature gradient ∇T are related by an equation as follows:

$$J_\mu=\sigma_{\mu\nu}(\mathbf{H})E_\nu-\beta_{\mu\nu}(\mathbf{H})\nabla_\nu T \ , \tag{2}$$

where $\sigma_{\mu\nu}(\mathbf{H})$ and $\beta_{\mu\nu}(\mathbf{H})$ are the conductivity tensor and the thermomagnetic tensor. The thermal emf coefficients ($\alpha_{\mu\nu}$) relate the temperature gradient to the field which appears as a result of cutting off the current ($\mathbf{J}=0$):

$$E_\mu=\alpha_{\mu\nu}(\mathbf{H})\nabla_\nu T, \quad \underline{\alpha}=\underline{\sigma}^{-1}\cdot\underline{\beta} \ . \tag{3}$$

Here we consider an isotropic homogeneous conductor in the shape of rectangular parallelepiped and in the magnetic field perpendicular to one of the planes (xy plane, the magnetic field is in the z direction). $\underline{\alpha}$ has the following form in this case:

$$\underline{\alpha}=\begin{bmatrix} \alpha_\perp & Q & 0 \\ -Q & \alpha_\perp & 0 \\ 0 & 0 & \alpha_{\parallel} \end{bmatrix} , \tag{4}$$

where $\alpha_\perp$ is the transverse magneto-Seebeck-coefficient and is expressed as

$$\alpha_\perp=\frac{\sigma_{xx}(\mathbf{H})\beta_{xx}(\mathbf{H})+\sigma_{xy}(\mathbf{H})\beta_{xy}(\mathbf{H})}{\sigma_{xx}(\mathbf{H})^2+\sigma_{xy}(\mathbf{H})^2} \ , \tag{5}$$

$\alpha_{\parallel}$ is the longitudinal magneto-Seebeck-coefficient and is expressed as

$$\alpha_{\parallel}=\frac{\beta_{zz}(\mathbf{H})}{\sigma_{zz}(\mathbf{H})} \ , \tag{6}$$

and Q is the Nernst-Ettingshausen coefficient. In a theoretical calculation of $\alpha_{\parallel}$ in the strong magnetic field, a Boltzmann equation can be formulated using a distribution function and a relaxation time because the electron motion parallel to the electric field $\mathbf{E}$ is not inhibited in the longitudinal configuration where $\mathbf{E}$ and $\mathbf{H}$ are parallel.[1,15] Contrary to this, the physical situation is completely different in the case of $\alpha_\perp$, because the electron motion parallel to the electric field is inhibited and fully quantum-mechanical formulation is needed for the detailed discussion of $\alpha_\perp$.[3–7] It should be mentioned here that the transverse and the longitudinal magnetoresistance, $\rho_\perp$ and $\rho_{\parallel}$, are expressed, respectively, as follows by use of the conductivity tensor components:

$$\rho_\perp=\frac{\sigma_{xx}(\mathbf{H})}{\sigma_{xx}(\mathbf{H})^2+\sigma_{xy}(\mathbf{H})^2} \ , \tag{7}$$

$$\rho_{\parallel}=\sigma_{zz}(\mathbf{H})^{-1} \ . \tag{8}$$

In the lowest order of scattering, it is well known that $\sigma_{xy}=-ne/H$ where n is the carrier concentration. Similarly, $\beta_{xy}=-nk_0\langle(\varepsilon-\zeta)\rangle/H$ in the lowest order of scattering, where k_0 is Boltzmann's constant and $\langle(\varepsilon-\zeta)\rangle$ means an average of the carrier energy relative to the Fermi energy ζ. Thus, the off-diagonal components, σ_{xy} and β_{xy}, are insensitive to the scattering while the diagonal components, σ_{xx} and β_{xx}, include a scattering term even in the lowest order.[15] Furthermore, as $\sigma_{xy}\gg\sigma_{xx}$ and $\beta_{xy}\gg\beta_{xx}$ are generally true in the quantizing magnetic fields, $\alpha_\perp$ and $\rho_\perp$ are expressed as follows from Eqs. (5) and (7), respectively:

$$\alpha_\perp\simeq\frac{\beta_{xy}(\mathbf{H})}{\sigma_{xy}(\mathbf{H})} \ , \tag{9}$$

and

$$\rho_\perp\simeq\frac{\sigma_{xx}(\mathbf{H})}{\sigma_{xy}(\mathbf{H})^2} \ . \tag{10}$$

From these expressions and the above-mentioned properties of the tensor components, it is understood that the MP oscillation can be expected in $\rho_\perp$ while it cannot be in $\alpha_\perp$. Results of some quantum-mechanical calculations of $\alpha_\perp$ and $\rho_\perp$ have been reported, which support the result of the simplified discussion given above.[24,25] Thus, it has been believed that the MP oscillation of $\alpha_\perp$ cannot be observed because the transverse magneto-Seebeck-coefficient $\alpha_\perp$ in a strong magnetic field may be monotonic with field and insensitive to the carrier scattering. As for the longitudinal case, on the other hand, rather large amounts of theoretical works were devoted to the MP oscillations, predicting the oscillatory structures in $\alpha_{\parallel}$.[1,26,27] In fact, many experimental works have been reported on the MP oscillation of $\alpha_{\parallel}$.[1,28]

It is evident that the experimental features of the MP oscillation of $\alpha_\perp$ summarized at the beginning of this section are not understood within the framework of the conventional theory of carrier scattering by LO phonons in a strong magnetic field. It is shown theoretically by Obraztsov[18] and others,[19] that the diamagnetism of the free carriers must be taken into account properly in the calculation of transverse magneto-Seebeck-coefficient $\alpha_\perp$ in strong magnetic field. According to Obraztsov,[18] the correction $\Delta\beta_{xy}$ to the thermomagnetic tensor due to the diamagnetism of carriers appears in β_{xy}, and $\Delta\beta_{xy}$ is expressed as

$$\Delta\beta_{xy}=c\frac{dM_z}{dT} \ , \tag{11}$$

where c is the light velocity and M_z is the magnetization. This correction is derived from the fact that the microscopic surface current determining the magnetism of conduction electrons in semiconductors makes a significant contribution to the macroscopic current density when a temperature gradient is present, as is shown in Ref. 18. An experimental test of this effect was also reported.[29]

On the other hand, it is known that the orbital diamagnetism is anomalously large due to the interband effect in some semimetals such as Bi.[30] The experimental fact that the MP oscillation of $\alpha_\perp$ is large particularly in the semimetallic substance of HgTe, and the importance of the orbital diamagnetism in the theory of $\alpha_\perp$, may suggest the existence of a new origin of the MP oscillation of $\alpha_\perp$ where electron-phonon coupling may affect $\alpha_\perp$ through the orbital diamagnetism, which has not been taken into account in the previous theory. As the MP oscillation of $\alpha_\perp$ is observed not only in semimetals but also in other semiconductors, the origin should be common to many semiconductors.

We propose here a possible mechanism which can explain the oscillatory change of the orbital diamagnetization due to the electron—LO-phonon coupling. In this model the orbital diamagnetism is considered to be affected by the electron-phonon coupling through the resonant magnetopolaron effects. The polaron effects in the magnetic field have been investigated in the cyclotron-resonance experiments of InSb by Larsen and others.[31–36] According to Larsen, the polaron ground-state energy $E(0)$ and the energy of the $n=1$ state $E(1)$, for weak coupling and in the limit of low magnetic field H, are given by

$$E(n)\approx(n+\tfrac{1}{2})\hbar\omega_c(1-\alpha/6)-\alpha\hbar\omega_0\ , \tag{12}$$

where $\hbar\omega_c$ is the cyclotron energy in the absence of electron-phonon interaction and α is the coupling constant. In the neighborhood where $\hbar\omega_c\approx\hbar\omega_0$, the energy for the $n=1$ Landau level is given by the implicit relation,

$$E(1)=(\tfrac{3}{2})\hbar\omega_c-\frac{\alpha\hbar\omega_0}{2\pi^2}\mathrm{P}\int d^3k\sum_n\frac{|H'_{n,1}(\mathbf{k})|^2}{E(0)+n\hbar\omega_c+\hbar\omega_0+\hbar^2k_z^2/2m_e-E(1)}\ , \tag{13}$$

where $H'_{n,1}(\mathbf{k})$ is a matrix element given in Ref. 33.

The numerical results of the theory for InSb are shown in, for example, Ref. 32 or 36. As is shown there typically, theoretical results of Landau levels in the presence of electron—LO-phonon interaction show that $E(1)$ changes for $\hbar\omega_c\approx\hbar\omega_0$. Such a change of Landau levels occurs also for $E(n)$ (for $n\geqq 2$) for $n\hbar\omega_c\approx\hbar\omega_0$. This situation of resonant magnetopolaron effect is clearly shown in a recent calculation of its energy for $n\leqq 11$ for bulk GaAs by Pfeffer and Zawadzki.[37] The conditions of $n\hbar\omega_c=\hbar\omega_0$ is more generally expressed by using the Eq. (1) for $m=0$ and neglecting the spins,

$$E_n-E_0=\hbar\omega_0\ . \tag{14}$$

Although the orbital diamagnetic moment is a thermodynamic average over all occupied states and therefore the change of the density of states must be taken into account, considering the drastic change of the Landau levels due to the resonant magnetopolaron effect, it is expected qualitatively that the orbital diamagnetism can be affected by the polaron effect under the condition of Eq. (14) in the strong magnetic field. If this is the case, we expect that the MP-type oscillation can be observed in $\alpha_\perp$ through an effect such as Eq. (11). It should be noted here that the experimentally observed relative amplitudes of the oscillations in $\alpha_\perp$ are on the order of 10^{-2}—10^{-3}, while the energy shift due to the resonant polaron effect reaches several percent. The effect of the renormalization of polaron masses for the orbital diamagnetism in semiconductors has been suggested in Ref. 38 for a weak-coupling case in the zero-magnetic field. Although the comprehensive quantum theoretical treatment of $\alpha_\perp$ that includes the resonant magnetopolaron effect is lacking at present, the experimental results presented in this paper may suggest a new effect of the electron—LO-phonon coupling other than a simple renormalization of polaron masses.

In the case of $\mathbf{H}||\mathbf{c}$ in p-type Te, it is known that the Landau-level scheme is very complicated[39] in addition to the complication of phonon structure due to the spiral chain structure of the Te crystal. The existence of rather large polaron effects in Te has been reported in the MP oscillation of transverse magnetoresistance $\rho_\perp$ by Miura *et al.*[21] In these situations, the MP oscillation extrema of $\alpha_\perp$ in $\mathbf{H}||\mathbf{c}$ may be shifted from the condition of Eq. (14).

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