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Ground state energy of the surface magnetopolaron in a polar crystal

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Abstract

Taking into account the interaction of an electron with surface optical (SO) phonons, we study the ground-state energy of the strong- and weak-coupling surface magnetopolaron in a polar crystal. The influence of the electron interaction with the strong- and weak-coupling surface optical phonons on the properties of the surface polaron in a magnetic field is investigated. The ground-state energy of a strong- and weak-coupling surface magnetopolaron is derived by using Tokuda linear-combination-operator method. Numerical calculations, for the AgCl crystal, as an example, are performed and some properties of the vibration frequency, the ground-state energy and the effective mass of the strong- and weak-coupling surface magnetopolaron in polar crystals are discussed.

Keywords: Surface magnetopolaron; Polar crystal; AgCl

1. Introduction

With the development of the magneto-optical technology, the properties of the polaron for polar crystals in a magnetic field of arbitrary strength have been of considerable interest [1–5]. In the early 1960s, Larsen [6,7] investigated the energy level of the polaron in magnetic field and the cyclotron-resonance problem of the piezopolaron. Then [8] he studied the cyclotron resonance of a two-dimensional (2D) polaron using the Rayleigh–Schrodinger perturbation theory (RSPT). Later [9] he proposed a novel fourth-order perturbation method to investigate the properties of 2D magnetopolarons. Wu et al. [10] calculated the ground-state energy of a Fröhlich optical polaron confined to two dimensions, placed in a perpendicular magnetic field by using the Feynman path-integral approach. The Feynman-model mass, the magnetization and the susceptibility are calculated as a function of the magnetic field strength for different values of the electron–phonon coupling. Subsequently, they [11] calculated the two-dimensional polaron cyclotron mass, which goes beyond the second-order perturbation theory. The present approach is based on a memory-function

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formalism and does not rely on a calculation of the Landau level. Kong et al. [12] have generalized Larsen perturbation method to treat the magnetopolaron in a semiconductor quantum well. Later, Osorio et al. [13] reported for the first time a theoretical calculation for the resonant donor impurity magnetopolaron in GaAs–$Ga_{1-x}Al_xAs$ quantum well structures. Employing Haga's perturbation method, Hu Ze et al. [14] derived an effective Hamiltonian for the interface magnetopolaron in polar crystals at zero temperature, in which the interactions of both bulk longitudinal optical (LO) phonons and interface (IF) phonons have been taken into account. Wei et al. [15,16] studied the induced potential and the self-energy of an interface magnetopolaron interacting with bulk longitudinal optical (BO) phonons as well interface-optical (IO) phonons using the Green-function method.

Huybrechts [17] proposed a linear-combination operator method, by which a strong-coupling polaron was investigated. Later, many workers [18,19] studied the strong-coupling polaron in many aspects by this method. On the basis of Huybrechts' work, Tokuda [20] added another variational parameter to the momentum operator and also evaluated the ground-state energy and effective mass of the bulk polaron. The ground-state energy and the cyclotron resonance frequency of the surface polaron in a magnetic field has been calculated by many methods. Many of them mainly concentrated their attention on the weak- and intermediate-coupling cases. However, the strong-coupling surface magnetopolaron in polar crystals has not been studied by using a linear combination operator method so far.

For the bulk polaron, the weak- and intermediate-coupling theories are applicable for the electron–bulk-LO–phonon coupling constant $\alpha < 6$ [21], whereas for the surface polaron this confinement is about 2.5 [22,23]. Hence, when the electron–SO–phonon coupling constant satisfied $\alpha_S > 2.5$, the strong-coupling theory must be applied.

In this paper, we apply the Tokuda' linear-combination operator method to study the influence of surface optical phonons on the properties of a strong- and weak-coupling surface magnetopolaron in polar crystals. The expression for the ground-state energy, cyclotron-resonance frequency and the effective mass of the surface polaron as a function of the magnetic field strength is obtained. Numerical calculations, taking a AgCl crystal as an example, are performed and properties of these quantities for the strong- and weak-coupling surface magnetopolaron in polar crystals are discussed.

2. Hamiltonian

The surface between a AgCl crystal and vacuum is perpendicular to the z-axis; the semiinfinite space $z > 0$ is occupied by the AgCl crystal, whereas the space $z < 0$ is a vacuum. A slow electron is placed inside the AgCl crystal at a distance $z\,(>0)$ from the surface. Assume that an external magnetic field $\boldsymbol{B} = (0, 0, B)$ (applied normal to the surfaces) exists and is described by a vector potential in the Landau gauge $\boldsymbol{A} = B(-y/2, 0, 0)$. Theoretical results [24] show that the surface layer of crystals may be regarded as pure 2D crystals if the distance from the surface is smaller than the radius of polarons. The effect of bulk phonons can be neglected, while the surface optical phonons are taken into account in the surface layer. The Hamiltonian of the electron–surface optical phonon system can be written as

$$H = \frac{1}{2m}\left(P_x - \frac{\beta^2}{4}y\right)^2 + \frac{1}{2m}P_y^2 + \sum_{\boldsymbol{q}} \hbar\omega_S a_{\boldsymbol{q}}^+ a_{\boldsymbol{q}} + \sum_{\boldsymbol{q}} (V_q e^{i\boldsymbol{q}\cdot\boldsymbol{\rho}} a_{\boldsymbol{q}} + \text{h.c.}), \tag{1a}$$

$$V_q = 2\pi i e\left(\frac{\hbar\omega_S}{4\pi\varepsilon S q}\right)^{1/2}, \tag{1b}$$

$$\frac{1}{\varepsilon} = \frac{\varepsilon_0 - 1}{\varepsilon_0 + 1} - \frac{\varepsilon_\infty - 1}{\varepsilon_\infty + 1}, \tag{1c}$$

$$\beta^2 = \frac{2e}{C}B, \tag{1d}$$

where $\boldsymbol{P} = (P_x, P_y)$ and $\boldsymbol{\rho} = (x, y)$ are momentum and the position vector, respectively, of an electron in a plane parallel to the surface. $a_{\boldsymbol{q}}^+$ and $a_{\boldsymbol{q}}$ are the creation and annihilation operators, respectively, of the surface optical phonon with a two-dimensional wave vector $\boldsymbol{q}$, ω_ℓ, ω_S and ω_T are the frequencies of the bulk LO, SO and bulk transverse optical phonons, S is the surface area of the AgCl crystal, and ε_0 (ε_∞) is the state (high-frequency) dielectric constant.

Following Tokuda [20] we also introduce the linear combination of the creation and annihilation operators b_j^+ and b_j to represent the momentum and position of the surface electron

$$P_j = \left(\frac{m\hbar\lambda}{2}\right)^{1/2}(b_{j^+} b_{j^+}^+ P_{0j}), \tag{2a}$$

$$\rho_j = i\left(\frac{\hbar}{2m\lambda}\right)^{1/2}(b_{j^+} b_j^+), \tag{2b}$$

where the suffix j refers to the x- and y-directions, λ and P_0 are a variational parameter, and b_j^+ and b_j are Bose operators satisfying the Bose commutative relation. Substituting Eq. (2) into Eq. (1a) and carrying out the unitary transformation

$$\mathscr{H} = U_2^{-1} U_1^{-1} H U_1 U_2, \tag{3}$$

where

$$U_1 = \exp\left(-iA\sum_{\boldsymbol{q}} a_{\boldsymbol{q}}^+ a_{\boldsymbol{q}}\, \boldsymbol{q}\cdot\boldsymbol{\rho}\right), \tag{4a}$$

$$U_2 = \exp\left(\sum_{\boldsymbol{q}} (a_{\boldsymbol{q}}^+ f_g - a_{\boldsymbol{q}} f_q^*)\right). \tag{4b}$$

Here f_q and f_q^* are variational parameters, and A is a parameter characterizing the coupling strength proposed by Huybrechts. In the unitary transformation U_1, $A = 1$ corresponds to the weak-coupling limit and $A = 0$ corresponds to the strong-coupling limit. The ground-state wave function of the system is $\phi = \varphi(\rho)|0\rangle$ where $\varphi(\rho)$ is the normalized surface magnetopolaron wave function. $|0\rangle$ is the zero phonon state, which satisfies

$$a_{\boldsymbol{q}}|0\rangle = b_j|0\rangle = 0. \tag{5}$$

Applying the transformations (4a) and (4b) to Hamiltonian (1a) and using the operator expressions (2a) and (2b), we can easily obtain the ground-state energy,

$$\begin{aligned} H_0 &= \langle 0|(U_1U_2)^{-1}H(U_1U_2)|0\rangle \\ &= \frac{\hbar\lambda}{2} + \frac{\hbar\lambda}{4}P_0^2 + \frac{\beta^4\hbar}{32m^2\lambda} + \sum_{\boldsymbol{q}} \hbar\omega_S|f_q|^2 \\ &\quad + \frac{A^2\hbar^2}{2m}\sum_{\boldsymbol{q}} q^2|f_q|^2 - A\hbar\left(\frac{\hbar\lambda}{2m}\right)^{1/2}\sum_{\boldsymbol{q}} |f_q|^2 \boldsymbol{P}_0\cdot\boldsymbol{q} \\ &\quad + \sum_{\boldsymbol{q}} (V_q^* f_q^* \mathrm{e}^{-(1-A)\,\hbar q^2/4m\lambda} + \text{h.c.}). \end{aligned} \tag{6}$$

The total momentum of the system can be written as

$$\boldsymbol{P}_T = \boldsymbol{P} + \sum_{\boldsymbol{q}} \hbar\boldsymbol{q} a_{\boldsymbol{q}}^+ a_{\boldsymbol{q}}\,. \tag{7}$$

Applying the unitary transformations (4a) and (4b) to the above expression and also using the momentum operator expression (2a), we obtain

$$\begin{aligned} \boldsymbol{P}_0 &= \langle 0|(U_1U_2)^{-1}P(U_1U_2)|0\rangle \\ &= \left(\frac{m\hbar\lambda}{2}\right)^{1/2}\boldsymbol{P} + (1-A)\sum_{\boldsymbol{q}} \hbar q|f_q|^2. \end{aligned} \tag{8}$$

The minimization problem is now carried out by the use of Lagrange's multiplier $\boldsymbol{u}$,

$$F(\lambda, \boldsymbol{P}_0, \boldsymbol{u}, f_q) = H_0 - \boldsymbol{u}\boldsymbol{P}_0\,. \tag{9}$$

$F(\lambda, \boldsymbol{P}_0, \boldsymbol{u}, f_q)$ may be called the variational parameter function. Minimizing Eq. (9) with respect to $\lambda, \boldsymbol{P}_0, \boldsymbol{u}, f_q$, we can determine these parameters and function. Then, inserting them into the expressions of H_0 and P, we can further evaluate the expectation value of H_0 and P for the ground state ϕ.

3. Weak- and strong-coupling limits

3.1. Weak coupling

In the unitary transformation, U_1 with $A = 1$ corresponds to the weak-coupling limit. Replacing $\sum_q$ by $(S/4\pi)^2 \int_0^\infty \int_0^{2\pi} q\, dq\, d\varphi$, although the calculation is straightforward, Eq. (9) can be written as

$$F(\lambda) = \frac{\hbar\lambda}{2} + \frac{\beta^2\hbar}{32m^2\lambda} - \frac{\pi}{2}\alpha_S\hbar\omega_S - \frac{\frac{1}{2}mu^2}{1-\frac{1}{8}\pi\alpha_S}. \quad (10)$$

Performing the variation in Eq. (10) with respect to λ, we get

$$\lambda = \frac{\omega_C}{2}, \quad \omega_C = \frac{eB}{mc}. \quad (11)$$

Inserting these parameters and functions into Eq. (8), we get the expectation value of the momentum for the ground state to be

$$\boldsymbol{P} = m\boldsymbol{u}/\left(1 - \frac{\pi}{8}\alpha_S\right). \quad (12a)$$

It is evident from the structure of this expression that $\boldsymbol{u}$ has the meaning of the velocity which may be regarded as the average velocity of the surface magnetopolaron, and the factor before $\boldsymbol{u}$,

$$m^* = \frac{m}{1-\frac{1}{8}\pi\alpha_S}, \quad (12b)$$

can be interpreted as the effective mass of the surface polaron in a magnetic field. Finally, ground-state energy can be expressed as

$$E_0 = \tfrac{1}{2}m^*u^2 + \tfrac{1}{2}\hbar\omega_C - \tfrac{1}{2}\pi\alpha_S\hbar\omega_S. \quad (13)$$

In Eq. (13), the first term is the kinetic energy of the surface magnetopolaron, the second term represents Landau ground-state energy of the surface polaron in a magnetic field and the third term is the self-trapping energy.

3.2. Strong coupling

In the unitary transformation, U_1 with $A = 0$ corresponds to the strong-coupling limit. Eq. (9) can be written as

$$F(\lambda, u) = \frac{\hbar\lambda}{2} - \frac{1}{2}mu^2 + \frac{\hbar\omega_C^2}{8\lambda} - \frac{\sqrt{\pi}}{2}\alpha_S\hbar\omega_S\left(\frac{\lambda}{\omega_S}\right)^{1/2} - \frac{\sqrt{\pi}}{8}\alpha_S\left(\frac{\lambda}{\omega_S}\right)^{3/2}mu^2. \quad (14)$$

Performing the variation in Eq. (14) with respect to λ, we obtain

$$x^4 - \tfrac{1}{2}\alpha_S(\pi\omega_S)^{1/2}x^3 - \tfrac{1}{4}\omega_C^2 = 0, \quad (15a)$$

where

$$\lambda = x^2. \quad (15b)$$

Inserting these parameters and functions into Eq. (8), we get the expectation value of the momentum for the ground state to be

$$\boldsymbol{P} = m\left(1 + \frac{\sqrt{\pi}}{4}\alpha_S\left(\frac{\lambda}{\omega_S}\right)^{3/2}\right)\boldsymbol{u} = m^*\boldsymbol{u}, \quad (16a)$$

$$m^* = m\left(1 + \frac{\sqrt{\pi}}{4}\alpha_S\left(\frac{\lambda}{\omega_S}\right)^{3/2}\right) \quad (16b)$$

is the effective mass of the strong-coupling surface polaron in a magnetic field. Finally, the ground-state energy of the strong coupling surface magnetopolaron can be expressed as

$$E_0 = \frac{1}{2}m^*u^2 + \frac{1}{2}\hbar\lambda + \frac{\hbar\omega_C^2}{8\lambda} - \frac{\sqrt{\pi}}{2}\alpha_S\hbar\omega_s\left(\frac{\lambda}{\omega_S}\right)^{1/2}. \quad (17)$$

In order to find the effective mass, the cyclotron resonance frequency and the ground-state energy of the strong-coupling surface magnetopolaron, we shall discuss the following two limiting cases.

3.2.1. Strong magnetic field

Under the strong magnetic field condition [9], $\omega_C \gg \omega_S$, Eq. (15a) can be written as

$$\left(\frac{\lambda}{\omega_C}\right)^2 - \frac{1}{4} = 0, \quad (18a)$$

$$\lambda = \tfrac{1}{2}\omega_C. \quad (18b)$$

Substituting Eq. (18) into Eqs. (16b) and (17), we have

$$m^* = m\left(1 + \frac{\sqrt{\pi}}{4}\alpha_S\left(\frac{\omega_C}{2\omega_S}\right)^{3/2}\right) \quad (19a)$$

$$E_0 = \frac{1}{2}m^*u^2 + \frac{1}{2}\hbar\omega_C - \frac{\sqrt{\pi}}{2}\alpha_S\hbar\omega_S\left(\frac{\omega_C}{2\omega_S}\right)^{1/2}. \quad (19b)$$

Eq. (19a) shows that for strong magnetic field the effective mass of the strong-coupling surface magnetopolaron is higher than the band mass. The first term in Eq. (19b) is the kinetic energy of the strong-coupling surface magnetopolaron, the second term is Landau ground state energy of the strong-coupling surface magnetopolaron, and the third term is the self-trapping energy.

3.2.2. Weak magnetic field

In the case of $\omega_C \ll \omega_S$, Eq. (15a) can be written as

$$\left(\frac{\lambda}{\omega_S}\right)^2 - \frac{\sqrt{\pi}}{2}\alpha_S\left(\frac{\lambda}{\omega_S}\right)^{3/2} = 0, \tag{20a}$$

$$\lambda = \frac{\sqrt{\pi}}{4}\alpha_S^2\omega_S. \tag{20b}$$

Substituting Eq. (20b) into Eqs. (16b) and (17), we have

$$m^* = m\left(1 + \frac{1}{32}\pi^2\alpha_S^4\right) \tag{21a}$$

$$E_0 = \frac{1}{2}m^*u^2 - \frac{\pi}{8}\alpha_S^2\hbar\omega_S + \frac{1}{2\pi\alpha_S^2}\left(\frac{\omega_C}{\omega_S}\right)\hbar\omega_C. \tag{21b}$$

From Eq. (21a), one can see that for the strong-coupling surface magnetopolaron in polar crystals, the increasing part of the effective mass is proportional to α_S^4 because of the strong coupling between the electron and surface optical phonon. In Eq. (21b), the first term is the kinetic energy of the strong coupling surface polaron in a weak magnetic field, the second term being proportional to the squared coupling constant α_S^2 is the coupling energy between the electron and the surface optical phonon, and the third term represents the coupling energy between the electron, the surface optical phonon and the magnetic field.

4. Results and discussion

The effective mass m^* and the ground-state energy E_0 of the weak-coupling surface magnetopolaron in polar crystals are given by Eqs. (12b) and (13). Eq. (12b) indicates that the effective mass is independent of magnetic field. Further it also indicates that there is only a magnetic field dependence of the Landau ground-state energy in Eq. (13), whereas the first and the third terms in Eq. (13) are independent of magnetic field because of the weak coupling between the electron and the surface optical phonon. From Eq. (12b) we also see that for weak electron–SO–phonon coupling when the electron–SO–phonon coupling constant takes very small values, Eq. (12b) can be expressed as

$$\frac{m^*}{m} = 1 + \frac{\pi}{8}\alpha_S + \frac{\pi^2}{64}\alpha_S^2\,. \tag{22}$$

This result is in agreement with the Feynman mass result and the Peeters mass result [11] at zero magnetic field.

To show more obviously the influence of the magnetic field on the properties of the strong-coupling surface polaron we perform a numerical evaluation by taking the polaron in the surface of a AgCl crystal as an example. In Table 1, the data for a AgCl crystal are given.

In the strong-magnetic-field case, the effective mass m^* and the ground-state energy E_0 of strong-coupling surface magnetopolaron are given by Eqs. (19a) and (19b). In order to express more clearly the influence of cyclotron frequency ω_C on the effective mass m^* of the surface magnetopolaron, numerical calculations for a AgCl crystal are performed and the results are given in Table 2. From Table 2, we can see that the effective mass of strong-coupling surface magnetopolaron in a AgCl crystal for the strong-magnetic-field case will increase with increasing cyclotron frequency; this result is in agreement with mass of Feynman polaron model of Ref. [10]. In Eq. (19b), note that the electron–phonon correction to the ground-state energy is proportional to $\alpha_S\sqrt{\omega_C\omega_S}$, which is in agreement with the result of Wu et al. (see Eq. (14) in Ref. [10]).

Table 1
The data for an AgCl crystal. All the parameters are taken from Ref. [25]

Material	ε_0	ε_∞	$\hbar\omega_S$ (meV)	α_S
AgCl	9.50	3.97	21.6	2.89

Table 2
Surface magnetopolaron effective mass for different values of the cyclotron frequency in an AgCl crystal

ω_C/ω_S	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
m^*/m	1.16	1.45	1.83	2.28	2.79	3.35	3.96	4.62	5.32	6.06	6.83	7.65

In the weak-magnetic-field case, the effective mass m^* and the ground-state energy E_0 of strong-coupling surface magnetopolaron are expressed by Eqs. (21a) and (21b). Eq. (21a) indicates that the effective mass is independent of magnetic field, whereas it will increase with increasing α_S. In Eq. (21b), the term $\frac{1}{8}\pi\alpha_S^2\hbar\omega_S$ is the ground-state energy of surface magnetopolaron in strong-coupling limit for $\omega_C \ll \omega_S$ except the first term in Eq. (21b); this result is smaller than the result of Wu et al. (see Eq. (15) in Ref. [10]).

Eq. (15) represents the vibration frequency of the strong-coupling surface magnetopolaron in polar crystals. From Eq. (15), one can see that the vibration frequency λ depends not only on the electron–SO–phonon coupling constant α_S and surface optical phonon frequency ω_S but also on the magnetic field B (or the cyclotron frequency for a rigid-lattice band mass ω_C). Fig. 1 shows the variation in the vibration frequency λ of the strong-coupling surface magnetopolaron in a AgCl crystal with the magnetic field B. From the figure, one can see that the vibration frequency λ will increase with increasing in the magnetic field B. The vibration frequency λ as a function of ω_C for a AgCl crystal is shown in Fig. 2. From Fig. 2, we can see that the vibration frequency λ will increase with increasing in the cyclotron frequency ω_C. One can also see that when $\omega_C = \omega_S = 0.327 \times 10^{14}\ s^{-1}$, $\lambda = 2.169 \times 10^{14}\ s^{-1}$, and when $\omega_C = 11.661\ \omega_S$, $\lambda = \omega_C = 3.813 \times 10^{14}\ s^{-1}$.

Eq. (16b) shows the effective mass of the strong-coupling surface magnetopolaron in polar crystals. From Eq. (16b), one can see that the effective

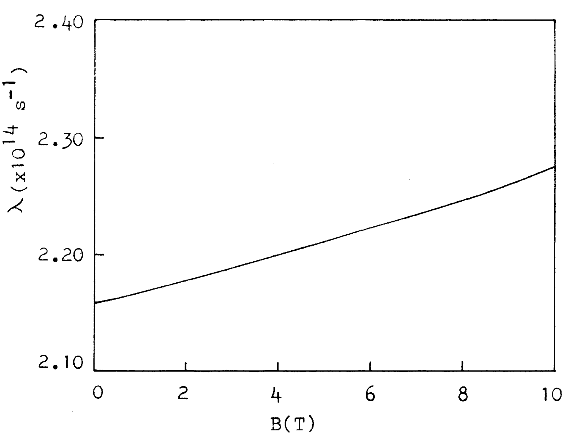

Fig. 1. The relation between λ and B in an AgCl crystal.

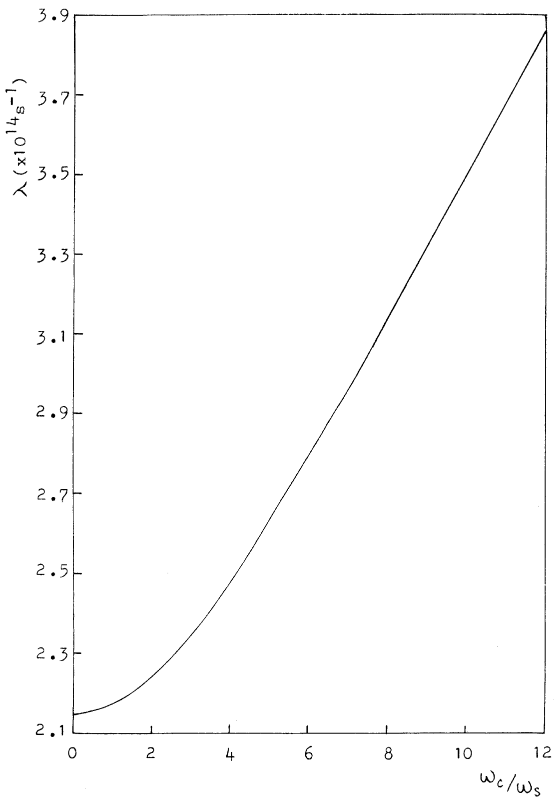

Fig. 2. The relation between λ and ω_C in an AgCl crystal.

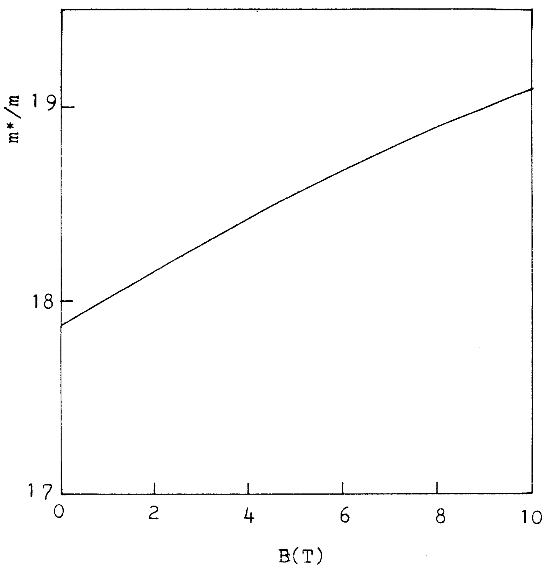

Fig. 3. The relation between m^*/m and B in an AgCl crystal.

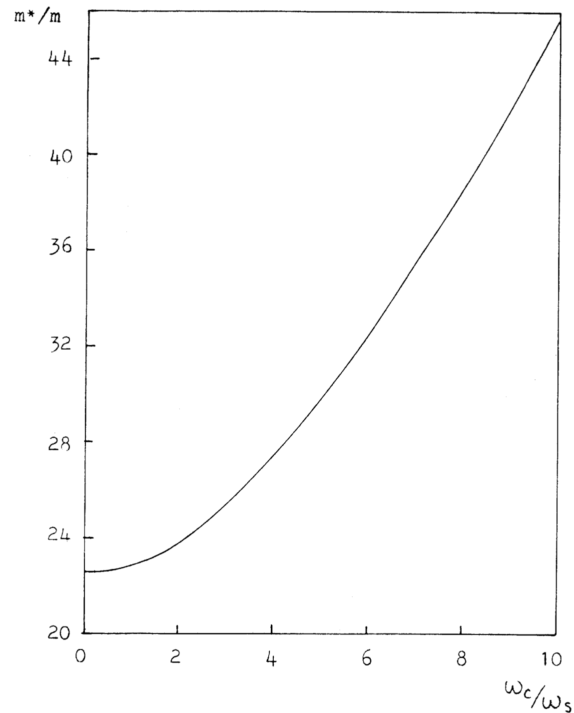

Fig. 4. The relation between m^*/m and ω_C in an AgCl crystal.

mass m^* depends not only on the electron–SO–phonon coupling constant α_S and surface optical phonon frequency ω_S but also on the magnetic field B. The dependence of the effective mass m^*/m of the strong-coupling surface magnetopolaron for a AgCl crystal on the magnetic field B is plotted in Fig. 3. From Fig. 3, we also see that the effective mass m^*/m increases with increase in magnetic field B. The effective mass m^*/m is almost linearly dependent on the magnetic field strength B. This result is in agreement with Larsen theoretical curve in a AgCl crystal [26]. Fig. 4 shows the relationship between the effective mass m^*/m of the surface magnetopolaron in a AgCl crystal and the cyclotron frequency ω_C. Note that the effective mass m^*/m increases with increase in ω_C; this result is in agreement with the mass of Feynman polaron model (see Table 1 in Ref. [10] for $\alpha = 4$).

Eq. (17) represents the ground-state energy of the strong-coupling surface magnetopolaron in polar crystals. It can be expressed as

$$E_0 = \frac{1}{2} m^* u^2 + E_{tr}, \tag{23a}$$

where

$$E_{tr} = -\frac{1}{2}\hbar\lambda - \frac{\hbar\omega_C^2}{8\lambda} + \frac{\sqrt{\pi}}{2}\alpha_S\hbar\omega_S\left(\frac{\lambda}{\omega_S}\right)^{1/2} \tag{23b}$$

is the self-trapping energy of the strong-coupling surface magnetopolaron. From Eq. (23b), one can see that the self-trapping energy E_{tr} of the strong-coupling surface magnetopolaron depends not only on the vibration frequency λ, the electron–SO–phonon coupling constant α_S and surface optical phonon frequency ω_S but also on the magnetic field B. Fig. 5 shows the relationship between the self-trapping energy E_{tr} of the strong-coupling surface magnetopolaron in a AgCl crystal and the magnetic field B. It can be noted from the figure that the self-trapping energy E_{tr} will decrease with increasing magnetic field B. The dependence of the self-trapping energy E_{tr} of the surface magnetopolaron in a AgCl crystal on the cyclotron frequency ω_C is plotted in Fig. 6. Fig. 6 shows that the self-trapping energy E_{tr} will decrease with increasing cyclotron frequency ω_C. In Eq. (15a), taking $\lambda = 2\times10^{14}\ s^{-1}$ and $\omega_S = 0.9\times10^{14}\ s^{-1}$ as examples, we perform a numerical calculation, and Fig. 7 shows the variation in the cyclotron

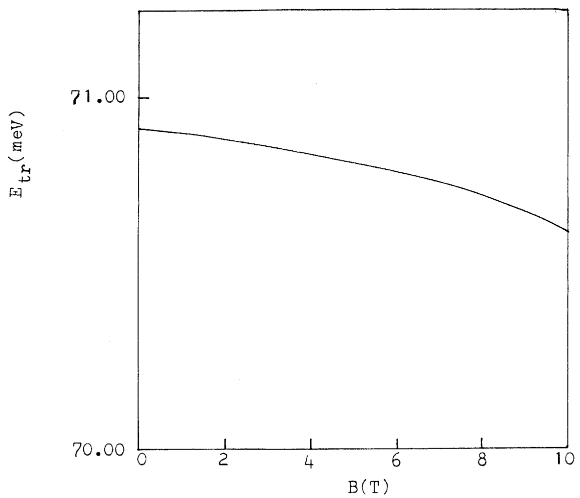

Fig. 5. The relation between E_{tr} and B in an AgCl crystal.

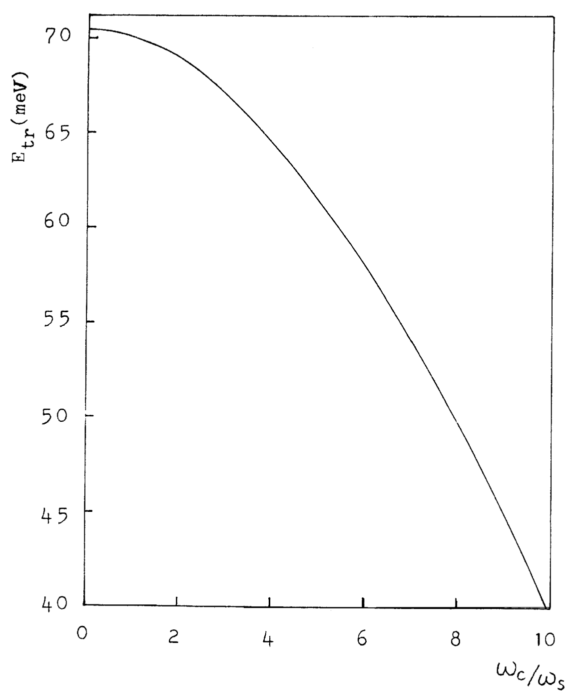

Fig. 6. The relation between E_{tr} and ω_C in an AgCl crystal.

frequency ω_C of the surface magnetopolaron in polar crystals with the electron–SO–phonon coupling constant α_S. From the figure we see that ω_C decreases with increase in the α_S.

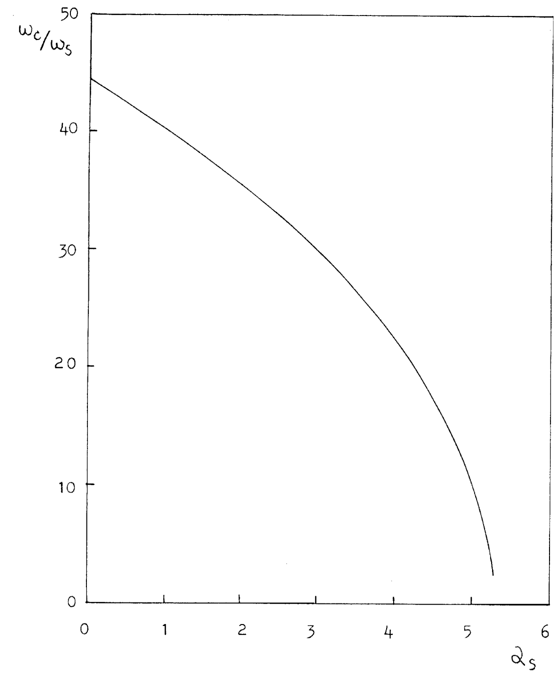

Fig. 7. Variation of ω_C with α_S in polar crystals.

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