Theory of photon-drag effect in bulk magnetic semiconductors

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The theory of the photon-drag effect in magnetic semiconducting crystals is considered using the *s-d* (or *s-f*) exchange model of interaction between the electron and the magnon. An equation is derived for the electric field generated by this effect. Numerical examples are given for $CdCr_2Se_4$ crystals.

I. INTRODUCTION

The advent of the laser has made it possible for us to investigate many new and interesting phenomena in semiconductors, both normal and magnetic. Among others are phonon[1-5] and magnon[6-9] amplification, harmonic generation, and photon-drag effect.[10-13] The photon-drag effect, in particular, arises from the transfer of momentum from photons to free carriers (either holes or electrons) in the absorption process through photon electron-phonon interactions.[13,14] As a result of the transfer of momentum, a net flow of charges appears in the direction of propagation of the laser wave. That is, a current of photovoltage effect can be observed.[13,14]

The theoretical basis of the photon-drag effect arises from the first-order terms of the matrix element of the free-carrier–photon-phonon interaction when the matrix elements are expanded in terms of the wave vector of the photons, and was first established by Grinberg[15] in germanium crystals and later by Yee[16] for polar crystals.

In the case of magnetic semiconductors, the magnons provide an additional channel to assist the free-carrier absorption[17] of laser radiation; at the same time the photon electron-magnon interaction may constitute the fundamental mechanism for the photon-drag effect in these materials.

It is the purpose of this paper to investigate theoretically the photon-drag effect in a magnetic semiconductor based upon the *s-d* exchange model of interaction between the magnon and the electron. The motivation for such a study is the development of high-mobility magnetic semiconductors such as $CdCr_2Se_4$ doped with Ag ($\sim 10^4\ \mathrm{cm^2/V\,sec}$).[18-21]

In the calculation that follows, we shall first find the change of the distribution function of the free carriers due to the photon-electron-magnon interaction, and then, using the Boltzmann transport equation, we will determine the electric field generated by the photon-drag effect.

II. CALCULATION

Our model for a magnetic semiconductor is that of an interacting conduction-electron localized-moment system.[22,23] The carriers and the localized moments interact by their exchange interaction which is taken to have the familiar *s-d* contact form. The total Hamiltonian of the system will comprise the conduction-electron part, the exchange-coupled local-moment part, and the interaction terms. We assume that the localized moments experience a ferromagnetic exchange interaction only with their nearest neighbors, and consider only the exchange part of the conduction-electron local-moment interaction, which will be represented by a spin-dependent contact potential. Also, since we are interested in studying the system below the Curie temperature, we shall introduce the magnon variables straightforwardly. Thus, in the second quantization formalism the total Hamiltonian is given by

$$\begin{aligned} H=&\sum_{\mathbf{p},\sigma} E_{\mathbf{p}\sigma}C^{\dagger}_{\mathbf{p}\sigma}C_{\mathbf{p}\sigma}+\sum_{\mathbf{k}}\hbar\omega b^{\dagger}_{\mathbf{k}}b_{\mathbf{k}}\\ &+M_{s\text{-}d}\sum_{\mathbf{p},\mathbf{k}}(C^{\dagger}_{\mathbf{p}+\mathbf{k},\uparrow}C_{\mathbf{p}\downarrow}b_{\mathbf{k}}+\mathrm{c.c.})\\ &-e/m_0c\sum_{\mathbf{p},\sigma}(\mathbf{A}_R\cdot\mathbf{p})C^{\dagger}_{\mathbf{p}\sigma}C_{\mathbf{p}\sigma}\ . \end{aligned} \tag{1}$$

Here,

$$E_{\mathbf{p}\sigma}=\mathbf{p}^2/2m-\hat{\sigma}JS/2 \tag{2}$$

and

$$\hbar\omega_{\mathbf{k}}=2ZIS\left[1-1/Z\sum_{\hat{\delta}}e^{i\mathbf{k}\cdot\hat{\delta}}\right] \tag{3a}$$

denote the electron and magnon energies, respectively, and

$$M_{s\text{-}d}=-J(S/2N)^{1/2}\ , \tag{3b}$$

where J is the exchange parameter between the localized spin and the conduction electron, N is the number of magnetic atoms, I is the exchange constant between the Z nearest-neighbor localized spins, and $\hat{\delta}$ is a vector to a nearest neighbor. $C_{\mathbf{p}\sigma}$ and $C^{\dagger}_{\mathbf{p}\sigma}$ are the usual annihilation and creation operators for conduction electrons. Here $\hat{\sigma}=+1$ for up conduction-electron moments and $\hat{\sigma}=-1$ for down moments. The $b_{\mathbf{k}}$ and $b^{\dagger}_{\mathbf{k}}$ are the magnon annihilation and creation operators. The last term in Eq. (1) represents the interaction of the electron and

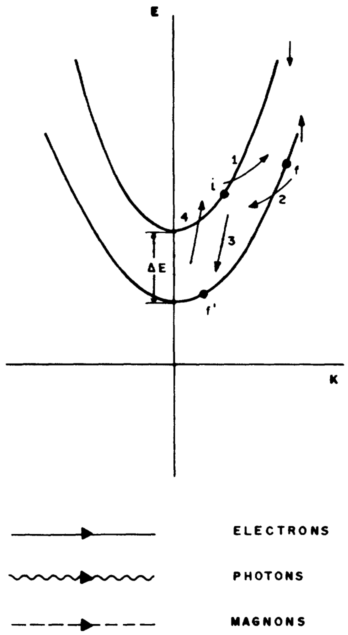


FIG. 1. Energy-band diagram showing the possible transitions that affect the distribution function of the electron at the energy state $E(k_1,\downarrow)=E+\Delta E/2$. $\Delta E=J_{s\text{-}d}\langle S\rangle$.

the radiation field with the vector potential $A_R=\mathbf{A}(\mathbf{r},t)+\mathbf{A}^*(\mathbf{r},t)$, where m_0 is the electron mass in free space.

From Eq. (1), we can calculate all the possible transitions which will affect the distribution function of the free carriers in the conduction subbands.

Figure 1 shows the possible transitions which satisfy the conservation of energy $E_f=E_i+\hbar\omega+JS\pm\hbar\omega_{\mathbf{k}}$ (arrows labeled 1 and 2) and $E_{f'}=E_i-\hbar\omega+JS\pm\hbar\omega_{\mathbf{k}}$ (arrows labeled 3 and 4). Here, $E_i=\hbar^2k_i^2/2m$, $E_f=\hbar^2k_f^2/2m$, and JS is the energy gap between spin subbands. The Feynman diagrams shown in Figs. 2 and 3 give the possible alternatives in which an electron can absorb (or emit) a photon with the participation of a magnon. The matrix elements for the processes shown in Fig. 1 are obtained using second-order perturbation theory given by the general expression

$$M=\sum_I\langle f|H_{e\text{-}m}|I\rangle\langle I|H_{e\text{-}r}|i\rangle/(E_i-E_I+i\eta) \quad (\eta\rightarrow 0)\ , \qquad (4a)$$

where $H_{e\text{-}m}$ and $H_{e\text{-}r}$ are given by the third and fourth terms of Eq. (1), respectively. Arrow 1 in Fig. 1, for instance, represents the absorption of the photon $\mathbf{q}$ by the electrons from an energy state $(E_i+JS/2)$ to $(E_f-JS/2)$ with the participation of a magnon $\mathbf{k}$. In

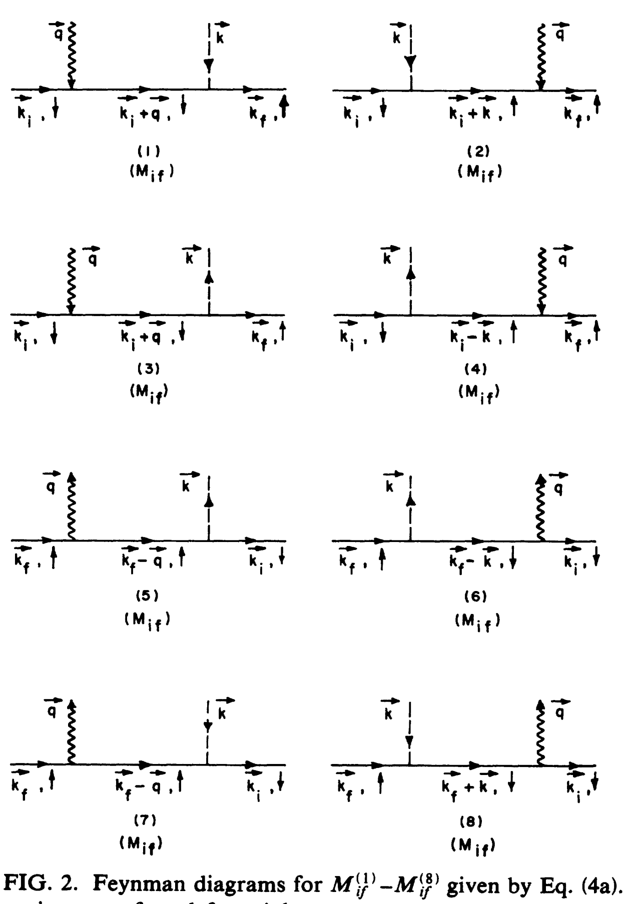


FIG. 2. Feynman diagrams for $M_{if}^{(1)}$–$M_{if}^{(8)}$ given by Eq. (4a). Time increases from left to right.

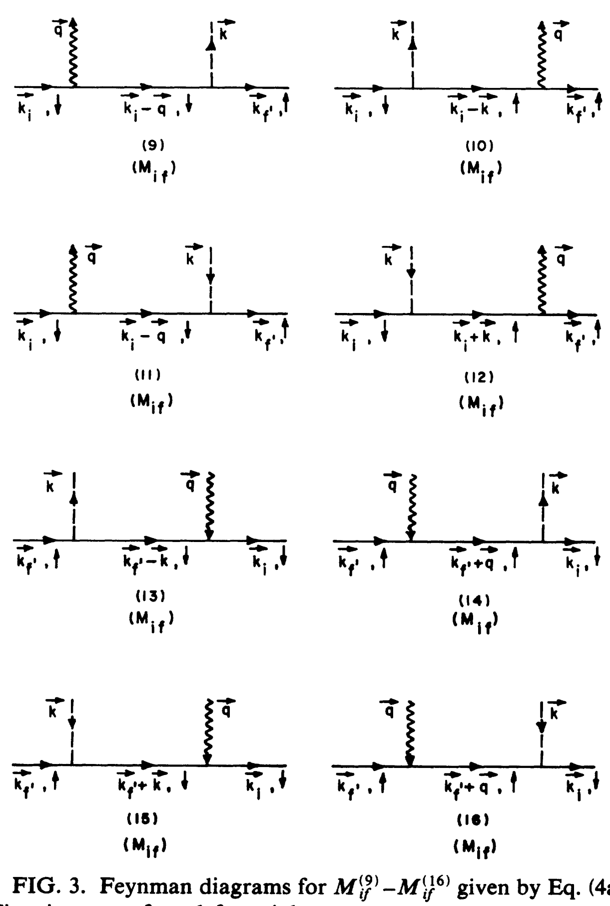


FIG. 3. Feynman diagrams for $M_{if}^{(9)}$–$M_{if}^{(16)}$ given by Eq. (4a). Time increases from left to right.

this case we can write, with the help of Eq. (4), one of the four possible matrix elements associated to this transition, namely

$$M_{if}^{(1)}=(eA/mc)M_{s\text{-}d}(n_{\mathbf{k}})^{1/2}(\lambda\cdot\hbar\mathbf{k}_i)\delta_{\mathbf{k}_f,k_i+\mathbf{q}+\mathbf{k}}\times[E(\mathbf{k}_i+\mathbf{q},\downarrow)-E(\mathbf{k}_i,\downarrow)-\hbar\omega]^{-1}\,, \tag{4b}$$

where λ is a unit polarization vector of the vector potential, A is the amplitude of the vector potential, and $\mathbf{q}$ is the wave vector of the photon. The other matrix elements for the electron transition processes shown in Fig. 1 can be constructed in a similar way.

In what follows, we will make use of the matrix elements as given by Eq. (4) to write the kinetic equation for the free-carrier distribution function due to the interaction of the photon, the magnon, and the electron from which the electric field generated by the photon-drag effect will be derived.

Accordingly, the following partial derivative of the electron distribution function in, say, the subband $\uparrow$ is given by

$$\partial f(\uparrow)/\partial t=(2\pi/\hbar)\sum_{\mathbf{k}_f}\sum_{\mathbf{k}}\left[\sum_{i=1}\partial f_i/\partial t\right]\,, \tag{5}$$

$$\begin{aligned}\partial f_1/\partial t=\{&f(\mathbf{k}_f,\uparrow)[1-f(\mathbf{k},\uparrow)]|M_{if}^{(5)}+M_{if}^{(6)}|^2\\&-f(\mathbf{k}_i,\downarrow)[1-f(\mathbf{k}_f,\uparrow)]|M_{if}^{(1)}+M_{if}^{(2)}|^2\}\\&\times\delta(E_f-E_i-\hbar\omega_{\mathbf{k}}-\hbar\omega-JS)\,,\end{aligned} \tag{6}$$

$$\begin{aligned}\partial f_2/\partial t=\{&f(\mathbf{k}_f,\uparrow)[1-f(\mathbf{k}_i,\downarrow)]|M_{if}^{(7)}+M_{if}^{(8)}|^2\\&-f(\mathbf{k}_i,\downarrow)[1-f(\mathbf{k}_f,\uparrow)]|M_{if}^{(3)}+M_{if}^{(4)}|^2\}\\&\times\delta(E_i-E_{f'}+\hbar\omega_{\mathbf{k}}-\hbar\omega+JS)\,,\end{aligned} \tag{7}$$

$$\begin{aligned}\partial f_3/\partial t=\{&f(\mathbf{k}_f,\uparrow)[1-f(\mathbf{k}_i,\downarrow)]|M_{if}^{(13)}+M_{if}^{(14)}|^2\\&-f(\mathbf{k}_i,\downarrow)[1-f(\mathbf{k}_{f'},\uparrow)]|M_{if}^{(11)}+M_{if}^{(12)}|^2\}\\&\times\delta(E_f-E_i+\hbar\omega_{\mathbf{k}}-\hbar\omega-JS)\,,\end{aligned} \tag{8}$$

$$\begin{aligned}\partial f_4/\partial t=\{&f(\mathbf{k}_{f'},\uparrow)[1-f(\mathbf{k}_i,\downarrow)]|M_{if}^{(15)}+M_{if}^{(16)}|^2\\&-f(\mathbf{k}_i,\downarrow)[1-f(\mathbf{k}_{f'},\uparrow)]|M_{if}^{(9)}+M_{if}^{(10)}|^2\}\\&\times\delta(E_i-E_{f'}-\hbar\omega_{\mathbf{k}}-\hbar\omega+JS)\,.\end{aligned} \tag{9}$$

In Eqs. (6)–(9), the processes in which an electron $(\mathbf{k}_f,\uparrow)$ is created are subtracted from the processes in which an electron $(\mathbf{k}_f,\downarrow)$ is destroyed. This difference gives the increase in $f(\mathbf{k}_f,\uparrow)$. Also, in Eqs. (6)–(9), we assign the factors f or $1-f$ (where f is the probability distribution function) as appropriate for each transition to accommodate the Pauli exclusion principle.

Substituting Eqs. (6)–(9) into Eq. (5) and carrying out the summation for $\mathbf{k}$, neglecting the magnon dispersion $(\omega_{\mathbf{k}}\cong\omega_M)$ and changing the summation on $\mathbf{k}_f$ to an integral, we obtain

$$\begin{aligned}\partial f(\uparrow)/\partial t=&(2\pi/\hbar)V/(2\pi)^3\{f(E_i-JS/2+\hbar\omega+\hbar\omega_M)[1-f(E_i-JS/2)](n_k+1)\\&\quad-f(E_i-JS/2)[1-f(E_i-JS/2+\hbar\omega+\hbar\omega_M)]n_k\}\\&\times(\hbar^2J^2S/2N)|eA/mc|^2\int d\mathbf{k}_fM_1\delta(E_f-E_i-\hbar\omega-\hbar\omega_M-JS)\\&+(2\pi/\hbar)V/(2\pi)^3\{f(E_i-JS/2+\hbar\omega-\hbar\omega_M)[1-f(E_i-JS/2)]n_k\\&\quad-f(E_i-JS/2)[1-f(E_i-JS/2+\hbar\omega-\hbar\omega_M)](n_k+1)\}\\&\times(\hbar^2J^2S/2N)|eA/mc|^2\int d\mathbf{k}_fM_1\delta(E_f-E_i-\hbar\omega+\hbar\omega_M-JS)\\&+(2\pi/\hbar)V/(2\pi)^3\{f(E_i-JS/2-\hbar\omega+\hbar\omega_M)[1-f(E_i-JS/2)]n_k\\&\quad-f(E_i-JS/2)[1-f(E_i-JS/2-\hbar\omega+\hbar\omega_M)](n_k+1)\}\\&\times(\hbar^2J^2S/2N)|eA/mc|^2\int d\mathbf{k}_fM_2\delta(E_i-E_f-\hbar\omega+\hbar\omega_M+JS)\\&+(2\pi/\hbar)V/(2\pi)^3\{f(E_i-JS/2-\hbar\omega-\hbar\omega_M)[1-f(E_i-JS/2)]n_k\\&\quad-f(E_i-JS/2)[1-f(E_i-JS/2-\hbar\omega-\hbar\omega_M)](n_k+1)\}\\&\times(\hbar^2J^2S/2N)|eA/mc|^2\int d\mathbf{k}_fM_2\delta(E_i-E_f-\hbar\omega-\hbar\omega_M+JS)\,,\end{aligned} \tag{10}$$

where

$$n_k=1/(e^{\hbar\omega_k/k_BT}-1),\quad f(\mathbf{k}_i,\uparrow)=f(E_i-JS/2)\,,$$

and

$$M_1=|[\lambda\cdot\mathbf{k}_i/(E(\mathbf{k}_i+\mathbf{q},\downarrow)-E(\mathbf{k}_{i'}\downarrow)-\hbar\omega)]+[\lambda\cdot\mathbf{k}_f/(E(\mathbf{k}_f-\mathbf{q},\uparrow)-E(\mathbf{k}_{f'}\uparrow)+\hbar\omega)]|^2\,, \tag{11a}$$

$$M_2=|[\lambda\cdot\mathbf{k}_i/(E(\mathbf{k}_i-\mathbf{q},\downarrow)-E(\mathbf{k}_{i'}\downarrow)+\hbar\omega)]+[\lambda\cdot\mathbf{k}_f/(E(\mathbf{k}_f+\mathbf{q},\downarrow)-E(\mathbf{k}_{f'}\uparrow)-\hbar\omega)]|^2\,. \tag{11b}$$

Proceeding further, provided the wave vector of the light $\mathbf{q}$ is small when compared to the average momentum of the electrons, we can expand M_1 and M_2 in terms of $\mathbf{q}$ in a series and retain only the zero- and first-order terms in the expression. One gets

$$M=M_1=M_2=(1/\hbar\omega)^2[\lambda\cdot(\mathbf{k}_f-\mathbf{k}_i)]^2+2(1/\hbar\omega)^2[\lambda\cdot(\mathbf{k}_f-\mathbf{k}_i)/m\hbar\omega][(\lambda\cdot\mathbf{k}_f)(\mathbf{q}\cdot\mathbf{k}_f)-(\lambda\cdot\mathbf{k}_i)(\mathbf{q}\cdot\mathbf{k}_i)] \ . \tag{12}$$

We now assume that the excitation energy of the photon is much higher than that of the magnon (i.e., $\hbar\omega \gg \hbar\omega_M$). Using this assumption, the approximation given in Eq. (12) for the matrix elements and using the coordinate system of Fig. 4, we obtain for the rate of change in the electron distribution function, after solving the integrals given in Eq. (10), the expression

$$\begin{aligned}\partial f(\uparrow)/\partial t=&(2\pi/\hbar)V/(2\pi)^3(2\pi)^3(\hbar^2J^2S/2N)|eA/mc|^2[(2n_k+1)\hbar\omega\partial f/\partial E_i]\\ &\times\{2\pi(1/\hbar\omega)^2[(2m/\hbar^2)^{5/2}/3][(E_i+\hbar\omega+JS)^{3/2}-(E_i-\hbar\omega+JS)^{3/2}]\\ &\quad+(2m/\hbar^2)^{5/2}[E_i(E_i+\hbar\omega+JS)^{1/2}-E_i(E_i-\hbar\omega+JS)^{1/2}]\cos^2\theta\\ &\quad+[64\pi m^2/\hbar^4(1/\hbar\omega)^3]q[E_i^{3/2}(E_i+\hbar\omega+JS)^{1/2}-E_i^{3/2}(E_i-\hbar\omega+JS)^{1/2}]\cos^2\theta\sin\theta\sin\phi\} \ ,\end{aligned} \tag{13a}$$

where use has been made of the approximation

$$\pm\hbar\omega\partial f/\partial E_i=f(E_i-JS/2\pm\hbar\omega)-f(E_i-JS/2) \ . \tag{13b}$$

Similarly, we can obtain an equation for the change of the electron distribution function in subband $\downarrow$, $\partial f(\downarrow)/\partial t$, which is the same equation as for the subband $\uparrow$ except that now the energy term JS in Eq. (13) is replaced by $-JS$.

Accordingly, by summing up the two contributions for both the two-spin subbands, we may obtain the final expression for the change in the distribution function of the electrons, namely,

$$\partial f/\partial t=\partial f(\downarrow)/\partial t+\partial f(\uparrow)/\partial t \ , \tag{14a}$$

$$\begin{aligned}\partial f/\partial t=&(2\pi/\hbar)V(2\pi)^3(\hbar^2J^2S/2N)|eA/mc|^2[(2n_k+1)\hbar\omega\partial f/\partial E_i]\\ &\times\{2\pi(1/\hbar\omega)^2[(2m/\hbar^2)^{5/2}/3][(E_i+\hbar\omega+JS)^{3/2}-(E_i-\hbar\omega+JS)^{3/2}\\ &\qquad+(E_i+\hbar\omega-JS)^{3/2}-(E_i-\hbar\omega-JS)^{3/2}]\\ &\quad+(2m/\hbar^2)^{5/2}[E_i(E_i+\hbar\omega+JS)^{1/2}-E_i(E_i-\hbar\omega+JS)^{1/2}+E_i(E_i+\hbar\omega-JS)^{1/2}-E_i(E_i-\hbar\omega-JS)^{1/2}]\cos^2\theta\\ &\quad+[64\pi m^2/\hbar^4(1/\hbar\omega)^3]q[E_i^{3/2}(E_i+\hbar\omega+JS)^{1/2}-E_i^{3/2}(E_i-\hbar\omega+JS)^{1/2}+E_i^{3/2}(E_i+\hbar\omega-JS)^{1/2}\\ &\qquad-E_i^{3/2}(E_i-\hbar\omega-JS)^{1/2}]\cos^2\theta\sin\theta\sin\phi\} \ .\end{aligned} \tag{14b}$$

Having obtained the rate of change of the electron distribution function, Eq. (14), we can now write the Boltzmann equation for the photon-drag effect as follows:[15]

$$e/\hbar[\varepsilon\cdot\nabla_k f_0(E_k)]-(f-f_0)/\tau+\partial f_p/\partial t=0 \ , \tag{15}$$

where $\partial f_p/\partial t$ is that given in Eq. (14). In Eq. (15), f_0 is the equilibrium distribution function of the electrons, τ is the relaxation time of the electrons in the magnetic semiconducting crystal, and ε is the electric field.

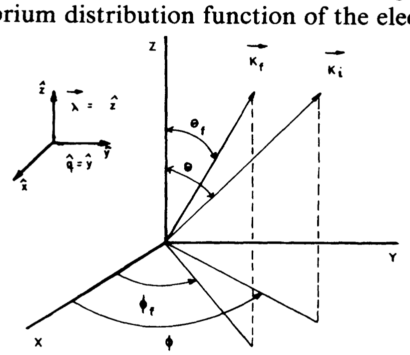


FIG. 4. Coordinate system used for the calculation.

We assume the distribution function f does not deviate very much from the equilibrium function f_0 by putting $f=f_0$ in Eq. (14). This assumption was found to be a good approximation in previous work.[15,16] We now assume that a constant uniform electric field ε is setup inside our semiconducting sample.

Under the foregoing assumptions the resulting current $\mathbf{j}$ can be written as[24]

$$\mathbf{j}=-e\hbar/m\sum_{\mathbf{k}_i}\{(-\tau/m)e(\varepsilon\cdot\mathbf{k}_i)(\partial f_0/\partial E_i)\mathbf{k}_i-\tau(\partial f_0/\partial k)\mathbf{k}_i\} \ , \tag{16}$$

where $\mathbf{k}_f$ labels the electron wave vector and E_i as before labels the bare electron energy. Substituting Eq. (14) with the f replaced by f_0 and doing the respective angular integrations, we obtain for the current along the y axis (the direction of propagation of the light wave) the expression

$$
\begin{aligned}
j_y \simeq & (2\pi/3)(e^2\hbar/m^2)V/(2\pi)^3 \\
& \times(2m/\hbar^2)^{5/1}\int dE_i E_i^{3/2}\tau(E_i)\varepsilon_y(\partial f_0/\partial E_i) - \tfrac{32}{25}[V/(2\pi)^3](me/\hbar^2)J^2S/(N/V)(eA/mc)^2 q(2n_k+1)(\hbar\omega)/(\hbar\omega)^3 \\
& \times\left\{\int dE_i E_i^{5/2}\tau(E_i)(\partial f_0/\partial E_i)[(E_i+\hbar\omega+JS)^{1/2}-(E_i-\hbar\omega+JS)^{1/2}\right. \\
& \left. +(E_i+\hbar\omega-JS)^{1/2}-(E_i-\hbar\omega-JS)^{1/2}]\right\} . \qquad (17)
\end{aligned}
$$

In Eq. (17), $|A|^2=2\pi CI/\varepsilon_\infty^{1/2}\omega^2$, I being the intensity of the laser light, and c the velocity of light.

If we now put $j_y=0$, we obtain the electric field generated by the photon-drag effect at the distance y in the crystal, namely,

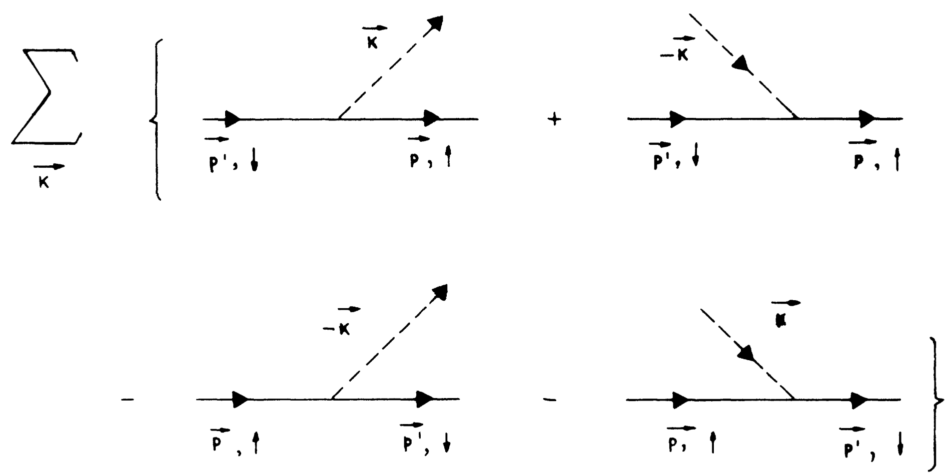
$$
\begin{aligned}
&\varepsilon_y \cong \tfrac{32}{5}\left\{[2^{-5/2}em^{1/2}J^2Sq(2n_k+1)I]/[(N/V)\varepsilon_\infty^{1/2}\hbar\omega(\hbar\omega^4)]\int dE_i E_i^{3/2}\tau(E_i)(\partial f_0/\partial E_i)\right\}F , \\
&F \equiv \int dE_i E_i^{5/2}\tau(E_i)(\partial f_0/\partial E_i)[(E_i+\hbar\omega+JS)^{1/2}-(E_i-\hbar\omega+JS)^{1/2}+(E_i+\hbar\omega-JS)^{1/2}-(E_i-\hbar\omega-JS)^{1/2}] .
\end{aligned} \qquad (18)
$$

Let us now evaluate Eq. (18) for the case of a degenerate magnetic semiconductor. In this case the electron distribution function is the Fermi distribution function which may be approximated by a step function. This is correct if the electron distribution function is not very much affected by the temperature which is valid at low temperatures. In order to perform the energy integration, we also need to know the energy dependence of the electron relaxation time $\tau(E_i)$.

In what follows we will determine this electron relaxation time due to the *s-d* interaction. This calculation is analog to those derived in the theory of resistivity.[25,26]

Accordingly, the kinetic equation for the electron distribution due to the *s-d* interaction is given schematically by

$\partial f_p(\uparrow)/\partial t =$



$$\times\ \delta(\vec{p}+\vec{K}-\vec{p}\,') . \qquad (19)$$

In Eq. (19) the processes in which an electron with spin ↑ is created are subtracted from the processes in which an electron ↑ is destroyed. This schematical equation can be converted to a mathematical equation with the help of the Fermi golden rule. One gets

$$\partial f_{\mathbf{p}}(\uparrow)/\partial t=(2\pi/\hbar)\sum_{\mathbf{k}}|M_{s-d}|^2\{[n_k(f_{\mathbf{p}+\mathbf{k},\downarrow}-f_{\mathbf{p},\uparrow})+f_{\mathbf{p}+\mathbf{k}}(1-f_{\mathbf{p},\uparrow})]\delta(E_{\mathbf{p}+\mathbf{k}}-E_{\mathbf{p}}-\hbar\omega_{\mathbf{k}}+JS)$$
$$+[n_{-\mathbf{k}}(f_{\mathbf{p}+\mathbf{k},\downarrow}-f_{\mathbf{p},\uparrow})-f_{\mathbf{p},\uparrow}(1-f_{\mathbf{p}+\mathbf{k},\downarrow})]\delta(E_{\mathbf{p}+\mathbf{k}}-E_{\mathbf{p}}-\hbar\omega_{-\mathbf{k}}+JS)\}\ , \qquad (20)$$

where the interaction vertex is given by Eq. (3b). It follows that Eq. (20) provides us with the mean lifetimes (assuming an equilibrium distribution for both electrons and magnons) given by

$$1/\tau=(2\pi/\hbar)\sum_{\mathbf{k}}|M_{s-d}|^2\{[n_{\mathbf{k}}+f_{\mathbf{p}+\mathbf{k}}]\delta(E_{\mathbf{p}+\mathbf{k}}-E_{\mathbf{p}}-\hbar\omega_{\mathbf{k}}+JS)+[n_{-\mathbf{k}}+(1-f_{\mathbf{p}+\mathbf{k}})]\delta(E_{\mathbf{p}+\mathbf{k}}-E_{\mathbf{p}}+\hbar\omega_{-\mathbf{k}}+JS)\}\ . \qquad (21)$$

Since we are mainly interested in the mean time of the electrons near the Fermi surface, the magnon energy and the JS energy terms are smaller than that of the electrons. Under this assumption we may admit elastic scattering for the latter, so that we may write $E_{\mathbf{p}+\mathbf{k}}\cong E_{\mathbf{p}}$. Assuming further that the magnon energy is smaller than the thermal energy, we may write ($\omega_{\mathbf{k}}\cong\omega_M$) $n_k\cong k_BT/\hbar\omega_M>1$. Under the foregoing simplifying assumptions, Eq. (21) is written approximately as

$$1/\tau\cong(4\pi/\hbar)\sum_{\mathbf{k}}|M_{s-d}|^2 n_k\delta(E_{\mathbf{p}+\mathbf{k}}-E_{\mathbf{p}})\ . \qquad (22)$$

Upon transforming the summation over $\mathbf{k}$ into an integral and performing the respective integrations, we finally obtain for the relaxation time of the electrons

$$\tau(E_i)=\hbar^5\omega_k/(8V|M_{s-d}|^2k_BTm^{3/2}E_i^{1/2})\ . \qquad (23)$$

Having obtained the electron relaxation time [Eq. (23)] which is a function of the bare electron energy, we are now able to evaluate Eq. (18) for the electric field due to the photon-drag effect. Accordingly, by substituting Eq. (23) into Eq. (18), approximating the electron distribution function by a step function, assuming as before that the final carrier energy differs sightly from the initial energy [Eq. (13b)] and doing the indicated integration we obtain

$$\varepsilon_y=\tfrac{28}{15}(2^{3/2})[VIem^{1/2}J^2Sq(2n_k+1)E_F](Nc\varepsilon_\infty^{1/2}\hbar^5\omega^4)^{-1}$$
$$\times[(E_F+\hbar\omega+JS)^{1/2}-(E_F-\hbar\omega+JS)^{1/2}$$
$$+(E_F+\hbar\omega-JS)^{1/2}-(E_F-\hbar\omega-JS)^{1/2}]\ , \qquad (24)$$

where E_F is the Fermi energy.

III. DISCUSSION AND CONCLUSIONS

Equation (24) is the expression for the electric field inside the magnetic semiconducting crystal due to the proton-drag effect. This field arises as a result of the transfer of momentum from photons to the free carriers through the photon free-carrier magnon interaction. The electron-magnon interaction here was assumed to be the s-d (or s-f) interaction. To get an order-of-magnitude estimate of the strength of this effect, we apply Eq. (24) to a semiconducting magnetic sample such as $C_dCr_2Se_4$.[8,27–29] Using $m=10^{-28}$ g, $\varepsilon_\infty=10$, $S=\frac{3}{2}$, $J\cong10^{-14}$ ergs, $E_F=5\times10^{-13}$ ergs, $N/V=10^{21}$ cm^{-3}, $\hbar\omega=2\times10^{-13}$ ergs (10.8-μm CO_2 laser), $T=50$ K ($T_c\cong128$ K), $\hbar\omega_k=10^{-15}$ ergs, and $I=1$ MW/cm^2, we find the electric field is

$$\varepsilon_y=25\ \text{mV/cm}\ .$$

By increasing further the laser intensity by, say, two orders of magnitude, we use Eq. (24) and find that in this case the electric field is

$$\varepsilon_y=0.25\ \text{V/cm}\ .$$

Because of the present-day available pulsed high-power lasers, the strength of this photon-drag effect can be made very large. In deriving the matrix elements $M_{if}^{(1)}-M_{if}^{(16)}$, we have left out the exact form of the electron-magnon interaction $M_{e\text{-}m}$. As a result, these matrix elements can be transformed to the case where the electron-magnon interaction is either the dipolar or the spin-orbit interaction (dropping the spin terms), respectively, by making a proper substitution for $M_{e\text{-}m}$. Therefore, the theory presented here is much more general than we indicated in the beginning. Furthermore since ε_y is directly proportional to J^2, this photon-drag effect could be useful as a tool of investigating the electron-magnon interaction in these materials. We finish by pointing out that, although our calculations presented above are for bulk magnetic semiconductors, the theory can easily be extended for the interesting case of quantum-well layered structures. In these structures the carriers are confined so as to behave as a quasi-two-dimensional electron gas, and size quantization effects begin to play an important role in determining their properties. The photon-drag effect in this case will accompany the free-carrier magnon-assisted absorption from electrons in these confined systems. This problem is being considered for a forthcoming paper.

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