R. M. White

Magnetic Field Dependence of Indirect Transitions in Ferromagnetic Semiconductors

Abstract: The optical absorption coefficient for magnetic semiconductors has been calculated for indirect transitions in which the intraband scattering arises from an s-d or s-f exchange interaction instead of the usual phonon mechanism. The temperature and magnetic field dependence of the resulting absorption coefficient are discussed.

The s-d or s-f exchange interaction between the conduction electrons and the localized moments of magnetic semiconductors is thought to be the origin of many of their unusual properties. One such example is the sensitivity of the paramagnetic Curie temperature of these materials to changes in carrier concentration. Another example is the large magnetoresistance in the vicinity of their Curie points. It has recently been proposed[1] that this interaction may also lead to indirect transitions in the optical absorption spectra of magnetic semiconductors. The purpose of this paper is to consider additional aspects of such indirect transitions. In particular, we shall investigate their low-temperature nature where magnon processes become important. We shall also consider the effect of an external magnetic field on such an indirect absorption edge at all temperatures.

Let us begin by briefly reviewing the essential features of the model used in Ref. 1. The semiconductor aspects of this model are characterized by a valence band and a conduction band. The conduction band minimum is assumed to occur at some point in the Brillouin zone other than that corresponding to the valence band maximum. This situation is illustrated in Fig. 1. The magnetic aspects arise from the presence of localized moments associated with the transition metal or rare-earth cations. Conduction band electrons, generated either by doping or by optically induced pair production, interact with the localized moments through the s-f or s-d exchange interaction. In the case of pair production the resulting hole will also,

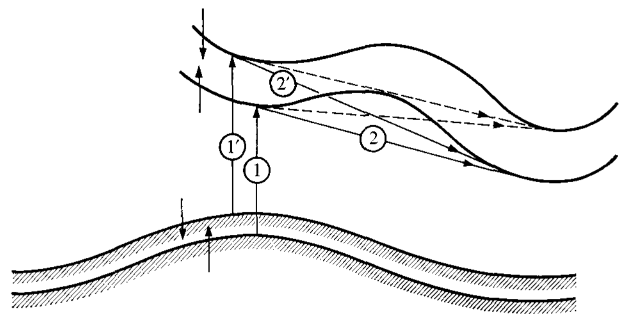

Figure 1 Schematic diagram of local moment fluctuation and magnon-assisted indirect transitions. (See Ref. 1 for detailed discussion).

in general, interact with the localized moments. The electron interaction, for example, has the form

$$\mathcal{H} = -\sum_{\mathbf{k},\mathbf{q}} J_{\mathbf{k},\mathbf{k}+\mathbf{q}}[S_{\mathbf{q}}^{z}(c^{\dagger}_{\mathbf{k},\uparrow}c_{\mathbf{k}+\mathbf{q},\uparrow} - c^{\dagger}_{\mathbf{k},\downarrow}c_{\mathbf{k}+\mathbf{q},\downarrow}) + S^{+}_{\mathbf{q}}c^{\dagger}_{\mathbf{k},\downarrow}c_{\mathbf{k}+\mathbf{q},\uparrow} + S^{-}_{\mathbf{q}}c^{\dagger}_{\mathbf{k},\uparrow}c_{\mathbf{k}+\mathbf{q},\downarrow}], \qquad (1)$$

where $c_{\mathbf{k}\sigma}$ is the annihilation operator for an electron with wavevector $\mathbf{k}$ and spin σ. The z-term in (1) associated with $\mathbf{q} = 0$ gives rise to a splitting of the spin-up and spin-down bands which, if $J_{\mathbf{k},\mathbf{k}}$ is the same for all $\mathbf{k}$, is equal to $2J\langle S^z\rangle$. In Fig. 1 this splitting is shown for a ferromagnetic exchange between the conduction electrons and the localized moments.

An indirect optical absorption can take place in several ways. For example, an electron at the valence band maximum might be virtually excited, to a point in the conduc-

The author is located at the Department of Physics, Stanford University, Stanford, California 94305.

tion band having the same wavevector. This electron would then be scattered by the interaction (1) to the conduction band minimum. Or, an electron might be promoted virtually to the conduction band minimum leaving behind a hole with this wavevector. This hole would then be scattered by the hole interaction, analogous to (1), to the valence band maximum.

The electron (or hole) scattering processes produced by the interaction (1) can take place either with or without an associated spin-flip. Above the Curie point both processes are comparable and give an absorption coefficient proportional to the generalized susceptibility $\chi(\mathbf{Q})$, where $\mathbf{Q}$ is the wavevector between the valence band maximum and the conduction band minimum. Below the Curie point the spin-flip process starts to become energetically unfavorable because of the spin-splitting of the conduction band as shown in Fig. 1. This is reflected in an absorption coefficient that is proportional to

$$\frac{(\hbar\omega - E_g - \hbar\Omega_{\mathbf{Q}})^3\langle S_{\mathbf{Q}}^+ S_{\mathbf{Q}}^- \rangle}{(\Delta E + J\langle S_z \rangle - \hbar\omega)^2}, \tag{2}$$

where $\hbar\Omega_{\mathbf{Q}}$ is the energy of a magnon with wavevector $\mathbf{Q}$. Since this corresponds to the emission of a magnon, it does not go to zero at low temperatures. (Notice that had we assumed the interaction between conduction electron spins and the localized moments to be antiferromagnetic this spin-flip process would involve magnon absorption and would go to zero with decreasing temperature.)

The nonspin-flip process, on the other hand, whose absorption coefficient, if one neglects the relatively small magnon energy, is proportional to

$$\frac{(\hbar\omega - E_g)^3\langle |S_{\mathbf{Q}}^z|^2 \rangle}{(\Delta E - \hbar\omega)^2}, \tag{3}$$

does go to zero with decreasing temperature. Therefore, as the temperature decreases below the Curie point the absorption is at first dominated by the nonspin-flip process whose decrease with temperature may give the absorption edge an apparent blue shift. Eventually, the absorption coefficient associated with this process becomes less than that associated with the energetically unfavorable spin-flip process. At this point, which depends upon the wavevector difference $\mathbf{Q}$, the absorption will become less temperature dependent.

In the simple two-band model we have been using, the application of a magnetic field should have the same effect on optical transitions as decreasing the temperature. Thus, in a direct transition the predominant effect of a field is to increase the splitting between the up- and down-spin bands thereby shifting the absorption toward the red. In an *indirect* transition the field has the additional effect of suppressing spin fluctuations which reduces the absorption coefficient. As in the case of a decreasing temperature this may appear as a *blue* shift.

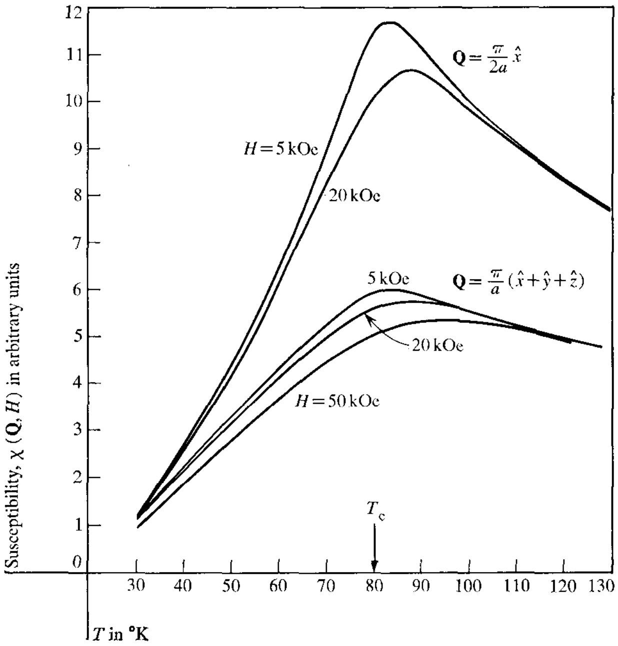

Figure 2 Generalized susceptibility as a function of temperature for various applied magnetic fields.

Let us consider the indirect transition in more detail. As we have indicated above, in the vicinity of the Curie point and above, the absorption coefficient is proportional to the longitudinal generalized susceptibility. Therefore, in the presence of a field H the quantity of interest is $\chi_{\parallel}(\mathbf{Q}, H)$. To compute this susceptibility we first consider the average spin in the presence of the exchange interaction as well as an applied field. This is given by the Brillouin function as

$$\langle S_i^z \rangle_0 = SB_S(x), \tag{4}$$

where the argument of the Brillouin function is

$$x = [NSJ(0)\langle S_i^z \rangle_0 - g\mu_B HS]/k_B T. \tag{5}$$

We now apply a perturbing field of the form $h\cos(\mathbf{Q}\cdot\mathbf{R}_i)$ and ask for the additional response δS_i^z. This is found by adding this field plus the appropriate exchange field to the argument of the Brillouin function and then expanding the Brillouin function. Applying a Fourier transform to the result for δS_i^z we obtain

$$\chi_{\parallel}(\mathbf{Q}, H) = \frac{3SCB_S'(x)/(S+1)}{T - [3S/(S+1)]B_S'(x)[J(\mathbf{Q})/J(0)]T_c}, \tag{6}$$

where $B_S'(x)$ is the derivative of the Brillouin function evaluated with the argument x. This susceptibility, in units of the Curie constant C, for $S = \frac{3}{2}$ and $T_c = 80°\mathrm{K}$, is shown in Fig. 2.

This figure shows that the larger Q becomes, the less sensitive the indirect absorption edge is to a magnetic field. It also shows that the field dependence is largest in the vicinity of the Curie point. Furthermore, this field dependence is further suppressed as the Curie point increases. This means that materials which are ferromagnetic semiconductors at room temperature, and, therefore, useful from a device point of view, will have indirect absorption edges that are relatively insensitive to applied magnetic fields.

The author is grateful to J. Timbie for numerous discussions and his assistance in evaluating the generalized susceptibility.

Reference

1. R. W. White, *Phys. Rev. Letters* **23**, 858 (1969).

Received November 6, 1969