Ferromagnetic semiconductor near the Curie temperature as a disordered medium

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We discuss the effect of magnetic-order fluctuations on the electric and optical properties of ferromagnetic semiconductors with strong *s-f* interaction. We consider the case when the exchange magnetization plays the role of a built-in fluctuation potential.

A strong *s-f* (*s-d*) interaction of the conduction electrons is frequently realized in ferromagnetic semiconductors in a wide band with localized magnetic moments. This leads to a large spin splitting of the conduction band below the magnetic Curie point T_C. The electron dispersion law in the magnetized band is given by

$$\epsilon(\mathbf{p}) = \epsilon_0(\mathbf{p}) \pm \frac{1}{2} I S_0 \frac{M(T)}{M_0}, \qquad (1)$$

where I is the exchange *s-f* integral, $M(T)$ and M_0 are the magnetizations at $T \neq 0$ and $T = 0$, respectively, and S_0 is the value of the localized spin. In experiment one observes a lowering of the edge of the band at $T < T_C$ by an amount on the order of 0.1–0.5 eV.[1,2] Near the Curie point, large inhomogeneous magnetization fluctuations $\Delta M(\mathbf{r})$ occur and should cause strong bending of the edge of the band. The conduction electrons are then in a random field, the potential-energy amplitude of which $\Delta U = \frac{1}{2} I S_0 (\Delta M / M_0)$ turns out to be much larger than the average kinetic energy ϵ of the electrons. The situation recalls the one existing in strongly doped and amorphous semiconductors,[3,4] and also when intense acoustic noise is excited in a semiconductor.[5] The case considered here differs in that the conduction band and the valence band are bent to different degrees, owing to the difference between the exchange integrals I; the random mangetic potential "breathes" slowly in time; the parameters of the potential depend significantly on the temperature and on the magnetic field.

Generally speaking, in the case of inhomogeneous magnetization it is necessary to introduce in (1) for the magnetization a nonlocal expression in terms of the radius R_0 of the exchange s-f interaction (to take into account the spatial dispersion of I). As the result it turns out that fluctuations with dimension $R < R_0$ yield a small splitting of the edge of the band. We shall take into account only the most important fluctuations with $R \gtrsim R_0$ assuming $R_0 \gg a$, and use the bent-band approximation (a is the interatomic distance).

The large fluctuations of the magnetic potential near T_C can affect radically the optical and electric properties of the semiconductor. In optics, the fluctuations are manifest in a smearing of the interband absorption edge, particularly also above T_C, and can lead as well to a broadening of narrow exciton lines and impurity radiative recombination lines.

With respect to the electric properties, electrons scattering by spin waves in semiconductors was considered earlier in[6].

The scattering of electrons by static magnetic fluctuations was also considered in[7] within the framework of the s-f model in second-order perturbation theory in the parameter $IS_0/\epsilon \ll 1$. It was shown that a resistance peak exists near T_C, and this correlates with the experimental data of[1]. The analysis in[7] is limited not only by the condition $IS_0 \ll \epsilon$, but also by the requirement $R \ll l$, where l is the mean free path. Under real conditions, the conditions $IS_0 \gg \epsilon$ and $IS_0(\Delta M/M_0) \gg \epsilon$ are more frequently realized, making perturbation theory inapplicable.

On the other hand, in ionic semiconductors with sufficiently high T_C ($T_C \gtrsim 100\,^\circ$K), the mean free path can become smaller than R_0, owing to the strong scattering by optical phonons, and should not depend in practice on T near T_C. (At an effective electron mass on the order of the free mass $m \sim m_0$, $T_C \sim 100\,^\circ$K, and a phonon Debye frequency $\omega_D \sim 300\,^\circ$K we have $l \sim 2$–$3a$.) In this case the magnetic fluctuations must be regarded not as a scattering potential, but as a built-in field, in which the electrons move in classical fashion. It is precisely this picture which we shall discuss in greater detail. The clearest manifestation of the onset of disorder at $T \sim T_C$ will occur in doped semiconductors with a specified electron density in the conduction band (e. g., a semiconductor with fully ionized shallow impurities). Above and below T_C, the conductivity in this case is activationless. Near T_C, the fluctuations grow, most electrons fall into the deepest fluctuation wells and turn out to be lower than the percolation level. [8] As a result, an activation energy appears in the conductivity and a resistance peak will be observed. We emphasize that the peak is connected not with the change in the mobility, as was assumed in[7], but with an exponential decrease of the electron concentration at the percolation level. It is typical, that in spite of the strong growth of the resistance near T_C, the microwave absorption by the free carriers should not change as a result of the constancy of the total electron concentration in the band.

The thermal fluctuations ΔM of the magnetization and ΔU of the potential energy are Gaussian. The mean-squared amplitude ΔM_R of a fluctuation with dimension R is estimated from the formula

$$\overline{\Delta M_R^2} \sim \frac{kT}{r_0^2 R} e^{-R/\xi} \qquad (2)$$

[r_0 is the radius of the exchange interaction of the localized spins; $\xi = r_0 |\alpha|^{-1/2}$ is the correlation radius; $\alpha = \alpha_0'(T - T_C)$]. At $R \sim R_0 \sim \xi \sim 10^{-7}$ cm, $r_0 \sim 10^{-8}$ cm, $S_0 = 7/2$, $kT \sim \epsilon \sim 10^{-2}$ eV and $I \sim 0.2$ eV we have $(\overline{\Delta U_{R_0}^2})^{1/2} \sim 0.2$ eV. The magnetic fluctuations give rise to an uneven redistribution of the electrons and to the appearance of Coulomb fields. The latter, however, are not significant at the characteristic $R \ll r_D$ (r_D is the electron Debye radius). It is also possible to disregard the formation of magnetofluctuons. [9] This is justified in semiconductors with sufficiently broad conduction band ΔE. At $\Delta E \sim 2$ eV and $I \sim 0.2$ eV, the change of the magnetization in the fluctuon region is $|\delta M| \sim 10^{-3} M_0$, i. e., it practically has no effect on the fluctuation potential.

The resultant activation energy is of the order of the rms energy $(\overline{\Delta U^2})^{1/2}$, so that for the parameters indicated above the electron concentration at the percolation level can decrease near T_C by a factor 10^3–10^4.

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