Phase diagram of a superdiamagnetic material

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It is shown that a ferromagnetic (FM) ordering occurs in a singlet-triplet current state of an excitonic dielectric, which precludes the appearance of superdiamagnetism. A superdiamagnetic (SDM) state can occur only if the spin-orbit interaction is taken into account. In this case a contact line exists between SDM and FM phases.

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1. The microscopic justification of the phenomenological model with spontaneous currents[1] is based on the possibility of a phase transition of a semimetal or a semiconductor to a state with a current-density wave (CDW, $\Delta_{SI} \neq 0$) or a spin flux-density wave (SFDW, $\Delta_{tI} \neq 0$).[2]

It is generally assumed in the analysis of a current state that a gap $\Delta_{SI}(\mathbf{r})$ and hence a nonuniform current are produced because of its superdiamagnetic properties. The response function for the total field in this case has a singularity that indicates the onset of an ideal diamagnetism. The finite susceptibility $\chi = M/H$ in this case is equal to $-1/4\pi$. In the analysis of the SDM phase the degeneration of current states ($T_{SI} = T_{tI}$) is disregarded in the absence of spin-orbit interaction and the onset of Δ_{SI} only is studied.[3,4]

2. There is, however, a basic difference between the state $\Delta_{SI} \neq 0$, $\Delta_{tI} \neq 0$, and the superdiamagnetic state.

The spectrum of single-particle excitations in the current state has the form

$$\omega_{1,2}^{\uparrow\downarrow}(\mathbf{k}) = \pm \sqrt{\epsilon_{\mathbf{k}}^2 + (\mathbf{k}\mathbf{p} - \Delta_{SI} \pm \Delta_{tI})^2}, \tag{1}$$

where $\mathbf{k}$ is the spectrum of the original, two-band system; the ∓ signs in front of the radical correspond to the subscripts 1, 2 and those under the radical correspond to the spin indices, and $\mathbf{p}$ is the matrix element of the momentum in the Luttinger-Kohn representation for bands of different parity.

The spin splitting of the spectrum accounts for the spontaneous momentum in the ordered phase $\Delta_{SI} \neq 0$, $\Delta_{tI} \neq 0$ for nonzero doping;

$$M = \mu_B \sum_{\mathbf{k}} \{ \operatorname{sgn}(\mathbf{k}\mathbf{p} - \Delta_{SI}) [f(\omega_1^{\uparrow}) + f(\omega_2^{\uparrow}) - f(\omega_1^{\downarrow}) - f(\omega_2^{\downarrow})]\}, \tag{2}$$

where

$$f(x) = [e^{\beta(x-\mu)} + 1]^{-1}.$$

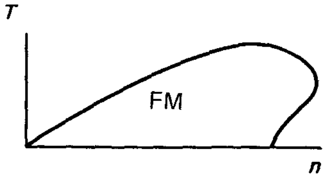

Fig. 1. Phase diagram of the model with spontaneous currents for $T_{SI} = T_{tI}$, expressed in terms of the temperature vs. level variables for doping.

The situation is analogous to that in an excitonic ferromagnet[5] but only in the current state. We note that the k-p hybridization in the spectrum does not affect the phase diagram constructed in Ref. 5 for an excitonic ferromagnet.

Thus, the singularity in the response to the external field χ, i. e., ferromagnetism, holds for $\Delta_{SI} \neq 0$, $\Delta_{tI} \neq 0$.

3. SDM cannot occur in the absence of spin-orbit interaction, which removes the degeneracy of current states[6]; a transition to the current state occurs on the line of formation of the FM phase, which was constructed in Ref. 5 (see Fig. 1).

4. The state with a CDW will ($T_{SI} > T_{tI}$) be more advantageous if the spin-orbit interaction is taken into account; the analogy with the excitonic ferromagnet makes it possible to construct a phase diagram of an SDM (see Fig. 2).

The properties of the response on the formation line $T_{SI}(n)$ of the SDM phase were investigated in Refs. 3 and 4. A transition from the SDM phase to the FM phase occurs as a result of decreasing the temperature ($n \neq 0$). The existence of a transition line of SDM to FM was predicted for the first time in this investigation.

The temperature range of the SDM phase decreases with increasing doping level.

5. In determining the direction of search for materials with SDM properties, we should take into account the aforementioned role of spin-orbit interaction, which removes the degeneracy of the states with a CDW and SFDW, and also the limited temperature range in which superdiamagnetism occurs.

The exchange of an SDM phase for an FM phase achieved by decreasing the temperature, which was observed in the experiment, is additional confirmation that the excitonic model of spontaneous currents is a mechanism for the onset of superdiamagnetism.

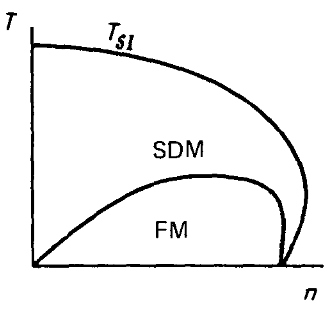

Fig. 2. Phase diagram of the model at $T_{SI} > T_{tI}$.

In conclusion, we note that allowance for inhomogeneity of the current state should not affect the qualitative results of this investigation, for example, a weak inhomogeneity whose magnitude is much greater than the freepath length of an electron.

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