Strain engineering in diluted magnetic semiconductors – the way of ferromagnetic T_c enhancement

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Recently (see Refs. [1] and [2] and references therein), great advances have been made in the problem of ferromagnetism (FMm) of *p*-doped diluted magnetic semiconductors (DMS's). The question about influence of different physical phenomena in DMS's on the critical temperature T_c of ferromagnetic (FM) phase transition is of prime interest for searching for the future study trends. After the Pashitskii and Ryabchenko prediction of FMm in DMS's [3], the competition between FM correlations mediated by indirect long-range spin-spin interaction and direct short-range antiferromagnetic (AFM) interaction is considered to be decisive in the formation of FM state in DMS's. In other words, to obtain FM state with high enough T_c , we need to inhibit the AFM contribution.

At large carrier concentrations n_c, the Friedel oscillations of carrier spin polarization become significant so that mean field approximation (MFA) applied in Ref. [3], becomes inapplicable. More thorough calculations with respect to Friedel oscillations (i.e. beyond (MFA)) corroborate above statement and show that in DMS undergoing FM phase transition n_c cannot exceed some critical value related to magnetic ions concentration n_i. The reason for that is the oscillations of the RKKY interaction at the scale of $1/k_F \sim n_c^{-1/3}$, which makes impossible long-range FM correlations if $k_F\bar{r} \geq 1$ ($\bar{r}$ is an inter-ion mean distance) [4, 5]. To properly account for above Friedel oscillations, which is indeed a spatial dispersion of inter-ion interaction, we developed so-called random field approximation (RFA) in Ref. [4].

Here we pay attention to the fact that transition from Heisenberg spin-spin interaction to Ising one, *i.e.*, exclusion of transversal spin components from Heisenberg Hamiltonian, decreases the system entropy and therefore can enhance T_c. For quantitative description of this effect we present a comparative analysis of the RFA theories for critical temperature T_c in Heisenberg and Ising models. This analysis has been made to determine the role of directional fluctuations (inherent to Heisenberg model) of localized spins in a random magnetic field. The uniaxial stresses in typical DMS structures grown on a substrate with some mismatch of lattice constants is shown to be the factor responsible for appearance of Ising-like interaction between magnetic ions spins. In other words, we expect that strain engineering can efficiently control the value of ferromagnetic phase transition temperature resulting from the hole-mediated exchange interaction between magnetic ions in DMS. The quantitative calculations predict the phase diagrams in variables T and ν separated FM DMS from non FM one (see Figure 1). It is shown that transition from Heisenberg to Ising interaction extends significantly the area with FM ordering of DMS.

We estimate now the increase of T_c for typical ferromagnetic DMS $Ga_{1-x}Mn_xAs$ deposited on GaAs and GaP substrates. The mismatch Δa of lattice constant a leads to biaxial strain that splits the valence band with deformation potential b=-1.7 eV by the value $\delta E_{1,2} = 2 \mid b\varepsilon`_{zz} \mid$ [6], where zz- component of strain tensor $\varepsilon`_{zz} = -2(\Delta a / a)c_{12} / c_{11}$ and the ratio of elastic moduli in GaAs $c_{12} / c_{11} = 0.453$. For x = 0.035 (or concentration $n_i = 7.76 \times 10^{20}$ cm^{-3}), the relative mismatch $|\Delta a / a| = 0.002$ for GaAs substrate and $|\Delta a / a| = 0.036$ for GaP substrate [7]. We can see that for GaAs substrate small valence-band splitting $\delta E_{1,2} \approx 6$ meV cannot suppress interaction of transversal Mn - spin components for typical concentration $n_c = 10^{20}$ cm^{-3} which corresponds to Fermi energy $\varepsilon_F \approx 80$ meV, whereas for GaP substrate $\delta E_{1,2} \approx 109$ meV $> \varepsilon_F$.

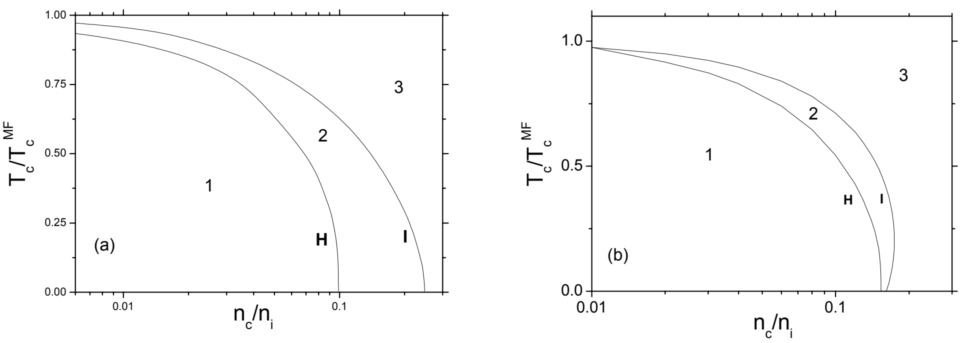

Fig. 1. The phase diagram of the systems under consideration. a) - non-Gaussian case for spin 1/2, b) Gaussian distribution function for spin 5/2. H - Heisenberg model, I - Ising model. Region 1 corresponds to FM state for both models, region 2 corresponds to FM state for Ising model and paramagnetic (PM) state for Heisenberg model, region 3 corresponds to PM state for both models

Thus, our mechanism predicts the enhancement of T_c for $Ga_{1-x}Mn_xAs$ on GaP substrate by the factor 1.64 (see Fig.1.b for $\nu = n_c / n_i = 0.13$) as compared to the same DMS but on GaAs substrate.

Note finally that here we considered the enhancement of T_c due to RKKY interaction only. But there are also other mechanisms, which can lead to appearance of ferromagnetism in DMS, see [2] for details. These mechanisms will be eventually reduced to our Hamiltonian with modified (*i.e.* non-RKKY) potential. Thus for quantitative discussion of these mechanisms it is sufficient to substitute the corresponding modified potential to our self-consistent equations.

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