Amplification of the induced ferromagnetism in diluted magnetic semiconductor

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Abstract. We consider (by the example of the structure Fe/Ga(Mn)As, investigated experimentally in [1]) magnetic properties of the planar nanostructure consisting of a ferromagnetic metal and a diluted magnetic semiconductor. In the framework of the mean field theory, it has been shown there occurs the considerable amplification of the ferromagnetism, induced by the ferromagnetic metal, due to the indirect interaction of magnetic impurities. That results in significant broadening the temperature range of the existence of the perceptible magnetization in the near-interface semiconductor area (run far beyond the interval limited above by the intrinsic Curie temperature of the magnetic semiconductor).

1. Introduction
One of the major roadblocks on the way to developing the semiconductor spintronics is now the lack of semiconductor materials and structures that would be ferromagnetic at the room temperature. Today, the record value of the Curie temperature is reached with the diluted magnetic semiconductor Ga$_{1-x}$Mn$_x$As ($x = 0.05 - 0.07$) and equals $T_C \approx 180$ K [2]. In this connection, the interest has been aroused in hybrid structures of the metal/semiconductor type whose magnetic properties are to the great extent defined by the high-temperature ferromagnetism of the metal being the part of the structure. For instance, in the recent paper [1] the planar structure Fe/Ga$_{1-x}$Mn$_x$As(100) has been investigated. It has been shown that the induced ferromagnetic state in the near-interface layer of the semiconductor film survives even at the room temperature. Antiferromagnetic exchange interaction [1] between Fe atoms and impurity Mn atoms in GaAs matrix is determined by the relevant effective magnetic field $H_{Fe}$ depending on the mutual disposition of a given Mn atom and different Fe atoms interacting with the latter. In addition, there is the indirect exchange interaction of the ferromagnetic nature between Mn atoms putting into effect via mobile charge carriers. That interaction is characterized by the effective exchange field $H_{Mn}$ depending on the distance $r_k$ ($k = 1, 2, \ldots$) between a given Mn atom and different Mn atoms interacting with the latter. Therewith, it is essential that the carrier mobility in the diluted magnetic semiconductor is so low (on the order of $10$ cm$^2$/V·s [3, 4]) that due to the collision broadening of the hole energy levels the system becomes to be effectively three-dimensional and there is no need to take into account any effect of the size quantization [5].

We show that the interference of both mentioned interactions, responsible for the magnetic ordering of Mn atoms, multiplies the effect of each mechanisms severally. In fact, the magnetic seeding which is the spin polarization of semiconductor magnetic atoms, induced by the ferromagnet, is significantly amplified due to the indirect interaction between those atoms. As a result, the Curie temperature, determining the existence of the ferromagnetism in the boundary region of the magnetic semiconductor, increases essentially.
2. Mean field approach

The magnetization in the boundary layer of the diluted magnetic semiconductor is parallel to the interface plane and significantly non-uniform along the direction perpendicular to the latter (z-axis). It is convenient to characterize such a non-uniform magnetization by the reduced local magnetization \( j(h) = M(h)/M_s \) (where \( h \) is the distance from the interface plane, \( M_s \) is the saturation magnetization).

In the framework of the mean field theory, it is defined by the equation

\[
j(h) = \tanh \left( \frac{1}{\tau} \left[ c_{Fe} \Phi(h) + c_{Mn} \int_0^{L_{Mn}} K(z, h) j(z) dz \right] \right),
\]

where \( c_{Fe} = 4 \pi n_{Fe} \ell_{Fe}^3 (J_{Fe}/J_{Mn}) \), \( c_{Mn} = 2 \pi n_{Mn} \ell_{Mn}^3 \) are structure parameters, \( \tau = kT/J_{Mn} \) is the reduced temperature. That is the non-linear integral equation determining the profile and the temperature dependence of the magnetization in the semiconductor part of the structure. It is non-local: the magnetization \( j(h) \) is defined by all points \( (0 < z < L) \) of the Ga(Mn)As film.
Figure 1. Spatial distributions of the local semiconductor magnetization $j_{Mn}(z)$ near the interface Fe/Ga(Mn)As at temperatures $\tau = 4 < \tau_C$ (left panel) and $\tau = 6 > \tau_C$ (middle and right panels) for $J_{Fe}/J_{Mn} = 2.5$. Mn↔Mn is the intrinsic magnetization of the semiconductor, Mn↔Fe is induced one, Mn↔Mn+Mn↔Fe is the induced magnetization amplified by the indirect interaction. The spatial dependence of the effective exchange interaction of Fe and Mn atoms: left and middle panels – Eq.(3), right panel – the linear approximation (see text).

3. Results
Numerical solution of Eq. (5) has been found, as in [5], by the successive-approximation method. Though we have kept in mind the concrete structure Fe/Ga$_{1-x}$Mn$_x$As [1], the qualitative character of our examination makes using exact values of parameters, governing the system behavior, to be surplus. Therefore, we accept that the constant $a$ of the (face centered cubic) Fe lattice is about half as the constant of the (body centered cubic) sublattice of Ga atoms (which are replaced by Mn atoms) and set $n_{Fe} a^3 = 2$, $n_{Mn} a^3 = 0.05$ (that corresponds to $x \approx 0.1$), and for other parameters accept the values $L_{Fe} = L_{Mn} = 7a$ [1], $\ell_{Fe} = a$, $\ell_{Mn} = 1.5a$. As for the ratio $J_{Fe}/J_{Mn}$, it has been varied over a wide range (see below).

Putting $c_{Fe} = 0$ in (5), one could find the temperature interval of the intrinsic (non-induced by the Fe film) ferromagnetism in Ga(Mn)As. The relevant Curie temperature occurs to be equal $\tau_C \approx 5$, or $kT_C = 5J_{Mn}$ (see below Fig. 2). For that case, in Fig. 1 (left panel, curve Mn↔Mn) the spatial distribution $j_{Mn}(z)$ of the local Mn magnetization at the temperature $\tau = 4 < \tau_C$ is shown. As one would expect, it is symmetric about the middle plane ($z = L/2$) of the semiconductor layer. In the same Fig. 1, one could see the spatial magnetization distribution of Mn atoms, induced by the their exchange interaction with Fe atoms only, without intrinsic indirect interaction (left panel, curve Mn↔Fe) for $J_{Fe}/J_{Mn} = 2.5$. Such an induced magnetization drops rapidly with moving away from the interface boundary Fe/Ga(Mn)As ($z = 0$). At last, the third curve (Mn↔Mn+Mn↔Fe) in the left panel of Fig. 1 is the result of the combined action of both mechanisms of magnetic ordering manifesting in the high amplification of the induced ferromagnetism by the indirect interaction of magnetic Mn impurities. The respective magnetization gain is especially high away from the boundary Fe/Ga(Mn)As ($z \geq L/2$), where the induced magnetization is enlarged up to fivelfold value.

It is remarkable that the substantial amplification of the induced magnetization remains even at temperatures being much higher the Curie temperature corresponding to the intrinsic ferromagnetism of Ga(Mn)As. The middle panel in Fig. 1, referring to the temperature $\tau = 6 > \tau_C$, demonstrates that the gain of the induced ferromagnetism even in this case remains equally
Figure 2. Temperature dependencies of the average magnetization $\langle j_{Mn}\rangle$ for the intrinsic (Mn↔Mn), induced (Mn↔Fe) and amplified combined (Mn↔Mn+Mn↔Fe) ferromagnetism of the considered structure. Left panel: $\ell_{Mn} = 1.5a$, $J_{Fe}/J_{Mn} = 0.5$, middle panel: $\ell_{Mn} = 1.5a$, $J_{Fe}/J_{Mn} = 5$, right panel: $\ell_{Mn} = 3a$, $J_{Fe}/J_{Mn} = 0.5$.

high, though away from the interface the absolute value of the magnetization drops somehow.

The magnetization gain in magnetic semiconductor stimulated by the spatially localized magnetic seeding is obviously demonstrated in the right panel of Fig. 1, where as the spatial dependence of the effective exchange interaction of Fe and Mn atoms we have chosen the linear approximation $\Phi(0) + \Phi'(0) h = 1 - h/2\ell_{Fe}$ of the function (3) (different from zero in the range $0 < h < 2\ell_{Fe}$ only). It is seen that even at the temperature $\tau = 6$, which is essentially exceeds the Curie temperature $\tau_C \approx 4$, magnetic ordering appears even in that region of the magnetic semiconductor where the induced seed magnetization is absent.

It is convenient to characterize the non-uniformly magnetized layer Ga(Mn)As by the average magnetization $\langle j_{Mn}\rangle = \langle 1/L \rangle \int_0^L j_{Mn}(z) dz$. Temperature dependencies of that value for the intrinsic (Mn↔Mn), induced (Mn↔Fe) and amplified combined (Mn↔Mn+Mn↔Fe) ferromagnetism are shown in Fig. 2 (left panel: $\ell_{Mn} = 1.5a$, $J_{Fe}/J_{Mn} = 0.5$, middle panel: $\ell_{Mn} = 1.5a$; $J_{Fe}/J_{Mn} = 5$). It is seen that significant magnetization of Ga(Mn)As remains even at the temperature which is by six (and more) times higher than the intrinsic Curie temperature. Such a giant expansion of the temperature interval of existing the ferromagnetism near the interface Fe/Ga(Mn)As has been experimentally observed in [1].

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