Heterogeneity of the magnetization of a thin film of a ferromagnetic semiconductor in the presence of an electric field

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The electrical manipulation of magnetism and magnetic properties has been achieved across a number of different material systems. For example, applying an electric field to a ferromagnetic material through an insulator alters its charge-carrier population.

The possibility of changing the spontaneous magnetization of a ferromagnetic semiconductor by applying an electric field was demonstrated in [1]. A thin film of a ferromagnetic semiconductor $(In_{0.97}Mn_{0.03})As$ 5 nm thick was placed on a substrate of other semiconductors.

In such a system, at a sufficiently high concentration Mn (on the order of several percent), the wave functions of the holes associated with neighboring ions begin to overlap, and a hole impurity band arises. Ferromagnetism is provided by the exchange interaction of holes with manganese ions by the Zener mechanism, i.e. indirect ferromagnetic interaction between ions is provided due to the *sd* -exchange of Vonsovsky-Ziner between holes and ions. The dependence of the density of states of a hole gas in the impurity band of energy, which overlaps noticeably with the valence band, is rather complicated. And for simplicity in the model calculation it was assumed that this dependence is the same as in a gas with some effective mass.

In this paper we consider the same theoretical model as in [2], but instead of not quite simple numerical calculations using approximate methods to derive analytical formulas for which the calculation is quite accessible in Mathematica package. This approach allows you to easily obtain possible changes in the results when changing parameters.

We introduce the density of manganese ions from the direction of the spin 5/2 and -5/2 in the easy magnetization axis $n_-^{5/2}(x), n_-^{-5/2}(x)$ and the density of holes with different projections on the easy axis $n_+^{1/2}(x), n_+^{-1/2}(x)$. The superscript here indicates the spin projection, and the bottom - at the sign of the charge. The density of the magnetic moment is determined by the hole densities

$$M(x,\Theta,E) = g\cdot\left(\frac{5}{2}\left(n_-^{5/2}(x)-n_-^{-5/2}(x)\right)+\frac{1}{2}\left(n_+^{1/2}(x)-n_+^{-1/2}(x)\right)\right),$$

$$n_-^{5/2}(x)-n_-^{-5/2}(x) = n_-\cdot\mathrm{Tanh}\left(\frac{\varepsilon_{ex}}{\Theta}\cdot\left(n_+^{1/2}(x)-n_+^{-1/2}(x)\right)\right),\quad n_+^{\pm 1/2}(z)=\frac{n_-}{2}\left(\frac{\mu^{\pm}(x)}{\varepsilon_F}\right)^{3/2},$$

which in turn are determined by the self-consistent potential $\varphi(x)$:

$$\mu^{\pm}(x)=\Phi_0-\varphi(x)\pm\varepsilon_{ex}\cdot n_-\cdot\mathrm{Tanh}\left(\frac{\varepsilon_{ex}}{\Theta}\cdot\left(n_+^{1/2}(x)-n_+^{-1/2}(x)\right)\right),$$

$$\frac{d^2\varphi}{dx^2}=-\frac{4\pi}{\chi}\cdot\left(n_+^{1/2}(x)+n_+^{-1/2}(x)-n_-\right),\quad \frac{d\varphi}{dx}\Big|_{x=0}=\frac{d\varphi}{dx}\Big|_{x=L}=-\frac{E}{\chi}.$$

When an electric field $E\neq 0$, the Curie temperature will vary along the thickness of the film because of the spatial inhomogeneity of the hole distribution. And this leads to a change in the Curie temperature for the average magnetization.

The graphical representation of the results has a natural physical interpretation.

Computing details will be presented in the poster report of the student A. Amirova.

References

[1] H. Ohno, D. Chiba, F. Matsukura, T. Omiya, E. Abe, T. Dietl, Y. Ohno & K. Ohtani. Electric-field control of ferromagnetism. Nature Vol 408 2000, 944-946.

[2] M. A. Kozhushner, B. V. Lidskii, V.S.Posvyansii, L.I.Trakhtenberg, Effect of an electric field on the magnetic characteristics of a nanoscale ferromagnetic semiconductor. JETP, 2016, Vol. 150, No.6, p.1227-1232