Long-Range Exchange Interaction Between Ferromagnetic Nanoparticles Embedded in Carbon Nanotubes

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Indirect exchange coupling mediated by the conduction electrons (Ruderman–Kittel–Kasuya–Yosida (RKKY) exchange) is studied in the multiwall carbon nanotubes (MWCNTs) of diameters of tens of nanometers with single domain ferromagnetic nanoparticles (FNPs) embedded inside. By adapting the Klinovaja-Loss (KL) model [Phys. Rev. B 87, 045422 (2013)] for single-wall carbon nanotube (CNT) and applying the parameters of MWCNTs, we show that the static spin susceptibility can propagate up to tens of micrometers. The main condition for the long-range exchange interaction is the adjustment of the Fermi level to the gap opened by the spin–orbit interaction (SOI). At typical diameters of the inner shell of MWCNTS of 20–30 nm, the required shift of the Fermi level is much smaller than that for single-wall CNT and does not exceed tens of meV. The proposed approach allows evaluating the energy of the exchange interaction between FNPs belonging to the same CNT. The obtained results open up good opportunities for the realization and implementation of MWCNT-based spintronic devices.

Index Terms— **Carbon nanotubes (CNTs), exchange interaction, ferromagnetic nanoparticles (FNPs), Ruderman–Kittel–Kasuya–Yosida (RKKY) exchange, spin–orbit interaction (SOI).**

I. INTRODUCTION

NANOPARTICLES of ferromagnetic materials have long been of interest because of their possible applications in high-density magnetic recording systems [1], biomedicine, drug delivery [2], and as building blocks for permanent magnets [3]. Ferromagnetic nanoparticles (FNPs) embedded in carbon nanotubes (CNTs) represent a special type of nanocomposites, in which the magnetic properties are determined not only by the size and magnetic characteristics of the nanoparticles, but also by their localization relative to the CNTs (outside, inside, between the walls) and the nature of the interaction between FNPs mediated by the CNT matrix [4]. In other words, the electronic properties of CNTs are also important for the overall magnetic properties of the nanocomposite, thus giving the possibility to consider such samples as a useful model object for studying magnetic interaction of FNPs through a conducting medium. For this, it is important to establish a relation between macroscopic and microscopic magnetic parameters of the system. In nanostructured ferromagnets, this dependence is described within the random magnetic anisotropy model (RAM), in which the spin system and, consequently, the main macroscopic characteristics (coercivity, susceptibility, saturation magnetization) are determined by such microscopic parameters as the exchange interaction constant, FNP magnetization, local magnetic anisotropy constant and so on [5], [6].

Recently, magnetic parameters, such as the exchange and anisotropy fields, effective constant of magnetic anisotropy, Bloch, and exchange constants in aligned arrays of semiconductor multiwall CNTs (MWCNTs) containing iron-based single domain FNPs, were determined in the framework of RAM by analyzing the law of the approach to saturation magnetization and corresponding modeling of correlation functions of the magnetic anisotropy axes [4], [7]. Presence of the interplay between the exchange interaction and magnetic anisotropy, as well as between random and coherent anisotropy, was established. In addition, the important role of magnetoelastic anisotropy in the case when a single FNP is localized inside a MWCNT has been revealed [8], [9]. It was found also that at liquid helium temperatures aligned MWCNT arrays with a low concentration of single domain FNPs embedded only inside nanotubes have relatively high values of the exchange field $H_{ex} \approx 4$ kOe [7], [10]. Moreover, the correlation function of the magnetic anisotropy axes, which best describes the approaching to saturation of the magnetization, is long-range and propagates over a distance of 150–200 nm that exactly coincides with the average distance between adjacent FNPs in a MWCNT [7].

One of the decisive factors for the emergence of the long-range magnetic order in CNT can be the indirect exchange coupling between the FNPs via the CNT conduction electrons [10]. Indeed, the exchange interaction between FNPs embedded in MWCNT could be due to the indirect exchange coupling of the Ruderman–Kittel–Kasuya–Yosida (RKKY) type mediated by the p-conduction electrons of the inner shell. However, there is still no thorough study of the mechanism of exchange in MWCNT, in which the distance between FNPs localized inside a single nanotube is hundreds of nanometers. The obtained preliminary estimations have

Manuscript received March 14, 2021; revised May 7, 2021; accepted July 29, 2021. Date of publication August 3, 2021; date of current version January 20, 2022. Corresponding author: S. L. Prischepa (e-mail: prischepa@bsuir.by).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TMAG.2021.3102403.

Digital Object Identifier 10.1109/TMAG.2021.3102403