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Low-temperature magnetic ordering in Co core/CoO shell nanoparticles on the copper surface

A.L. Danilyuk [a], E.S. Nazarenka [a], S.A. Vorobyova [b], J.A. Fedotova [c], S.L. Prischepa [a,*]

[a] Belarusian State University of Informatics and Radioelectronics, 220013, Minsk, Belarus
[b] Research Institute for Physical Chemical Problems of Belarusian State University, 220030, Minsk, Belarus
[c] Institute for Nuclear Problems of Belarusian State University, 220030, Minsk, Belarus

ABSTRACT

Cobalt/cobalt oxide nanoparticles electrochemically deposited onto a copper surface revealed an unusual behavior of the coercivity and exchange bias at liquid helium temperature [V.G. Bayev et al., Appl. Surf. Sci. 440 (2018) 1252–1260], pointing out the necessity of careful consideration of magnetic properties at these temperatures. Here, it is shown that the approach based on the random anisotropy model and analysis of law of the approach to magnetic saturation adopted for the two-dimensional (2D) magnetic system allows obtaining the correlation function of the magnetic anisotropy axes in real space, as well as the exchange, random and coherent anisotropy magnetic fields. The long-range correlation in the magnetic anisotropy axes and the oscillating character of the correlation function is the characteristic feature, suggesting the important role of the interplay between the exchange bias and random anisotropy on the one hand and indirect exchange coupling via the conducting electrons of copper and magnetic dipole interaction, on the other.

1. Introduction

Nanoparticles (NPs) of ferromagnetic (FM) metals are of paramount interest nowadays for both fundamental research and various applications. Suffice it to mention their use in catalysis [1], as an effective carrier for drugs delivery toxic for tumor cells [2], as well as for local therapy employing a magnetic *ac* field [3]. In addition, FM NPs with high magnetization and great specific power loss are considered as a potential candidate for use in wastewater treatment [4]. As for magnetoelectronic and spintronic applications, such NPs are used in magnetic memory devices [5], as a promising basis for creating highly efficient microwave radiation absorbers [6,7], tuning of the magnetic vortex dynamics [8], realizations of the transfer of spin ordering over macroscopically long distances via a conducting medium [9,10].

For many spintronic applications, the fabrication and investigation of two-dimensional (2D) magnetic structures is a very relevant task [11, 12]. The static magnetic properties of such low-dimensional systems, as well as their dynamic behavior and the associated functionality are most directly related to spin properties. Currently, there are unique tools that allow visualizing the spin structure at the nanoscale [13]. On the other hand, it is possible to predict the spin texture in low-dimensional materials using numerical simulations. Main parameters that need to be evaluated in this case are magnetic exchange interaction and magnetic anisotropy. It is their values that ultimately determine the spin texture.

Novel 2D magnetic materials both with intrinsic magnetic ground state and induced magnetic moment, such as graphene [14], topological insulators [15], silicene [16], phosphorene [17], ZnO [18,19], Cr-based van der Waals crystals [20,21], etc. provide a very perspective platform to design various nanohybrids for spintronic applications [11,12]. However, there are still many serious problems in 2D materials, such as stability to moisture, oxygenation and temperature, scalability of wafers and low operation temperatures, much less than the room temperature. These disadvantages significantly limit the widespread use of 2D magnetic materials in real devices.

An alternative way to create 2D magnetic structures is to form nanocomposites consisting of ultrathin film or NPs of magnetic material on the surface of a non-ferromagnetic conducting substrate [22–25]. In this case, it is possible to combine the advantages of magnetism at small sizes with the ability to tune the ordered state of 2D ferromagnet by means of a conductive substrate.

Methods for obtaining ultrathin films of ferromagnetic metals on conductive substrates are currently quite well developed [22–24]. However, the deposition of magnetic metal particles on conductive substrates is still a challenge. Generally, magnetic NPs are formed by chemical, physical or chemical/physical methods which yield free NPs, as well as NPs embedded in various host materials and particles attached to the surface of conducting solids. In the latter case, most of the technological processes for obtaining NPs are simply not applicable. For

* Corresponding author.
E-mail address: prischepa@bsuir.by (S.L. Prischepa).

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