

## A Study of the Properties of Core/Shell/Shell Ag/FeCo/Ag Nanoparticles

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**Abstract**—The properties of heterophase core/shell/shell Ag/FeCo/Ag nanoparticles synthesized via a plasma method that are promising for biological applications are studied. As is established, the core/shell/shell Ag/FeCo/Ag nanoparticles exhibit a superparamagnetic state at room temperature that allows one to manage the hyperthermia process. The magnetic characteristics of core/shell/shell Ag/FeCo/Ag nanoparticles are interpreted by assuming partial oxidation of the surface layer of a ferromagnetic FeCo shell and formation of the antiferromagnetic  $\text{Co}_x\text{Fe}_{1-x}\text{O}$  layer on the FeCo surface. The interaction between the surface antiferromagnetic  $\text{Co}_x\text{Fe}_{1-x}\text{O}$  layer and the ferromagnetic FeCo shell causes the emergence of the exchange bias in Ag/FeCo/Ag nanoparticles.

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### INTRODUCTION

In recent years, magnetic plasmon-resonant (PR) hybrid nanosized particles (HNPs) have received particular attention of researchers due to their promising properties that can be applied in biomedicine for drug targeting, cancer treatment, enhancement of the topographic contrast [1–4], magnetic separation, and image processing [5]. Targeted delivery with PR HNPs is based on their bioconjugation; i.e., any biomolecules (DNA/RNA, proteins, oligosaccharides, and others) can be adhered to these nanoparticles and delivered to the prescribed site of the organism. Owing to the high extinction and scattering cross section of PR HNPs, their luminosity exceeds by many times that of other marks. The unique optical properties of PR HNPs are referred to surface plasmon resonance, or excitation of surface plasmons with visible and IR light.

One of the most promising PR HNPs are core/shell/shell (C/S/S) Ag/FeCo/Ag nanoparticles [5–9]. Nanosilver meets the requirements for materials in this field to the greatest degree due to the lowest plasmon losses in the UV and visible spectral ranges. For synthesis of these HNPs [5–9], the FeCo and Ag particles were combined in the same heteronanostructure possessing the magnetic and plasmon properties. The main concept of C/S/S Ag/FeCo/Ag nanoparticle structure is that the Ag core ensures the localized surface plasmon resonance and inhibits the oxidation of a ferromagnetic FeCo shell because of the electron transfer from Ag core to FeCo shell [5–8]. The outer

Ag shell plays a key role in the prevention of oxidation of the intermediate FeCo shell and allows the HNP surface to be modified via the metal–thiol interaction. As was assumed in [8, 9], the magnetic properties of PR HNPs are affected significantly by oxidation of the FeCo shell. Nevertheless, better understanding of the properties of C/S/S Ag/FeCo/Ag NPs necessitates their comprehensive study.

In the present work, the PR HNPs are examined via X-ray photoelectron spectrometry (XPS), X-ray diffraction (XRD), superconducting quantum interference (SQUID), magnetometry, and Mössbauer spectroscopy.

### EXPERIMENTAL

#### *I. Synthesis of C/S/S Ag/FeCo/Ag NPs*

The C/S/S Ag/FeCo/Ag NPs were obtained in accordance with a technique described in [5, 7, 8]. Two types of solutions were prepared. The first of them contained 0.2 mmol of iron(III) acetylacetonate [ $\text{Fe}(\text{acac})_3$ ] (Sigma-Aldrich), 0.2 mmol of cobalt(II) acetylacetonate [ $\text{Co}(\text{acac})_2$ ] (Sigma-Aldrich), 1 mL of oleylamine (OLA) (Sigma-Aldrich), and 2 mL of toluene (Wako Pure Chemical). The second solution included 0.1 mmol of silver nitrate ( $\text{AgNO}_3$ ) (Sigma-Aldrich), 1 mL of OLA, and 1 mL of toluene. A mixture of 0.1 mmol  $\text{AgNO}_3$ , 1.0 mmol 1,2-hexadecandiol (HDD) (Sigma-Aldrich), 10 mmol OLA, 8 mmol oleic acid (OA) (Sigma-Aldrich) and 10 mL tetra eth-