ISSN 1063-7761, Journal of Experimental and Theoretical Physics, 2018, Vol. 126, No. 1, pp. 115–125. © Pleiades Publishing, Inc., 2018.
Original Russian Text © A.M. Esmaeili, A.N. Useinov, N.Kh. Useinov, 2018, published in Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki, 2018, Vol. 153, No. 1, pp. 137–149.

ELECTRONIC PROPERTIES OF SOLID

Dependences of the Tunnel Magnetoresistance and Spin Transfer Torque on the Sizes and Concentration of Nanoparticles in Magnetic Tunnel Junctions

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Received February 4, 2017

Abstract—Dependences of the tunnel magnetoresistance and in-plane component of the spin transfer torque on the applied voltage in a magnetic tunnel junction have been calculated in the approximation of ballistic transport of conduction electrons through an insulating layer with embedded magnetic or nonmagnetic nanoparticles. A single-barrier magnetic tunnel junction with a nanoparticle embedded in an insulator forms a double-barrier magnetic tunnel junction. It has been shown that the in-plane component of the spin transfer torque in the double-barrier magnetic tunnel junction can be higher than that in the single-barrier one at the same thickness of the insulating layer. The calculations show that nanoparticles embedded in the tunnel junction increase the probability of tunneling of electrons, create resonance conditions, and ensure the quantization of the conductance in contrast to the tunnel junction without nanoparticles. The calculated dependences of the tunnel magnetoresistance correspond to experimental data demonstrating peak anomalies and suppression of the maximum magnetoresistances at low voltages.

DOI: 10.1134/S1063776118010168

1. INTRODUCTION

The authors of [1] proposed to fabricate a new type of spintronic devices, namely, STT-MRAM memory cells based on magnetic tunnel junctions (MTJs) with a low critical switching current density ($J_c \approx 4.2 \times 10^3$ A/cm^2) at room temperature. A MgO insulating layer was deposited in a disperse medium with embedded Fe nanoparticles with various concentrations. One of the methods of embedding nanoparticles in the insulating layer is based on low-rate plasma-assisted deposition. Nanoparticles grow from nuclei through the process of atomic clustering [2–5].

The authors of [2] synthesized and studied the MTJ with magnetic anisotropy in the plane of layers based on the Ta(10)/$Ir_{22}Mn_{78}$(25)/$Co_{70}Fe_{30}$(3.5)/Mg(0.8)/MgO(2.8)/$Co_{70}Fe_{30}$(7)/Ta(10) nanostructure, where the numbers in parentheses are the thicknesses of layers in nanometers (see supplemental information in [2]). The MgO insulating layer of this structure contained embedded $Co_{70}Fe_{30}$ nanoparticles. The complete nanostructure with a SiO_2 substrate had the form SiO_2/Ta(10)/$Ir_{22}Mn_{78}$(25)/$Co_{70}Fe_{30}$(3.5) / MgO(2.5) / $Co_{70}Fe_{30}$(t_{NP}) / Mg(0.8)/MgO(2.5)/$Co_{70}Fe_{30}$(7)/$Ir_{22}Mn_{78}$(15)/Ta(10). Nanostructures were characterized by nominal thicknesses (sizes) t_{NP} of nanoparticles, which varied from 0.25 to 0.75 nm. These values were determined from transmission electron microscopy (TEM) images. The corresponding average diameters of nanoparticles from (1.53 ± 0.4) nm to (3.2 ± 0.7) nm were estimated in terms of three parameters: the electric capacitance of spherical nanoparticles, the blocking temperature of the magnetic moment of nanoparticles, and the diameter distribution function of nanoparticles in the MgO layer that is constructed from TEM images. Indeed, nanoparticles have arbitrary sizes and their distribution in the barrier can be controlled by the deposition rates, the material of the SiO_2 substrate, and annealing.

The measurements of the tunnel magnetoresistance (TMR) in [2, 4] show an anomalous increase in the TMR or its suppression at low applied voltages. These anomalies were observed at low temperatures ($T \approx 2.5$ K). In particular, the suppression of the TMR (a sharp decrease at zero voltages) was explained by the Kondo effect at the tunneling regime with the sizes of nanoparticles $t_{NP} < 0.7$ nm although unusually high peaks of the TMR appearing at low voltages were