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Magnetization reversal of ferromagnetic nanoparticles induced by a stream of polarized electrons

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ABSTRACT

The remagnetization of ferromagnetic Fe_3O_4 nanoparticles of several thousand cubic nanometers by spin-polarized current is investigated. For this purpose, magnetite nanoparticles are synthesized and deposited on a conductive nonmagnetic substrate. The remagnetization is conducted in high-vacuum scanning tunneling microscope (STM). The STM tip from magnetized iron wire constitutes one electrode while the ferromagnetic nanoparticle on the graphite surface represents the second electrode. The measured threshold value of remagnetization current (I_{thresh}=9 nA) is the lowest value of current at which remagnetization occurs. The change in nanoparticle magnetization is detected by the effect of giant magnetic resistance, specifically, the dependence of the weak polarized current ($I < I_{thresh}$) on the mutual directions of magnetization of the electrodes. The results indicate essential difference with available literature data on the influence of polarized current on magnetic moment of small ferromagnetic nanoclusters. The peculiarities of size dependence of the observed effects are explained.

1. Introduction

The dependence of current between two ferromagnetic electrodes separated by a thin insulating layer or a nonmagnetic metal on the mutual orientation of the magnetizations in the electrodes, i.e. the effect of giant magnetic resistance (GMR), has been known since 1988 [1,2]. This effect is widely used for reading in magnetic information recording systems. In 1996, Slonczewski [3] proposed a possible theoretical solution which was somehow the inverse problem of remagnetization of magnetic domain by polarized current, i.e. by flow of electrons with a preferred spin direction. The study considered the current as a ballistic flight of electrons from one ferromagnetic electrode to another.It allowed for the interaction of the spin magnetic moment of current electrons, which is parallel to the magnetic moment of the ferromagnetic cathode, with the magnetic moment of the ferromagnetic anode. Such an interaction may result in a change in the direction of anode magnetization. At about the same time, Berger discussed the possibility of a magnon excitation in a ferromagnetic material by the polarized current [4].The study allowed for the excitation of a magnon that leads to a reduction of domain magnetization on one magnetic moment of the electron. The possibility of domain remagnetization by the current in a massive ferromagnetic was also investigated theoretically [5]. The modified Landau–Lifshitz kinetic equation was applied for characterization of the domain remagnetization. This modified equation took into account the interaction of the magnetic moment of polarized current with the domain magnetic moment. Such an interaction may cause a change in the stationary domain magnetization.

The possibility of massive magnetic domain remagnetization by polarized current has been demonstrated experimentally [6–8]. The observed transverse dimension was on the order of microns, and the thickness was ~10 nm. Thus polarized current was introduced through a point contact, causing the rotation of magnetization in the (Co–Cu)N multilayer sandwiches [6]. A switch in the orientation of the magnetic moments in (Co–Cu–Co) sandwich structure was also observed for perpendicular electric currents throughout the domain plane [7]. In a subsequent study [8] the change of magnetic domain polarization was attributed to the diffusion current of polarized electrons through the non-magnetic conductor from another ferromagnetic.

The standard procedure often used to study and change nanoparticle magnetization is the scanning probe microscope, typically the Atomic Force Microscope (AFM) or the Scanning Tunneling Microscope (STM), with its own magnetization. For example, the remagnetization was studied of an ordered array of nanoparticles with a diameter 5–20 nm and a height of about

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100 nm consisting of cobalt and iron–chromium alloy, utilizing the field of the permanent magnet on the probe of the atomic force microscope [9]. This technique was demonstrated to allow both the diagnosis of magnetization vectors as well as study their effect readily. A magnetic STM chromium tip indicated double chains of atoms, consisting of a few tens of atoms located on the surface of Ir (001) with (5×1) reconfiguration and its characteristic magnetization vector [10]. This result established the change of chain magnetization.

There is an alternative approach to study magnetic nanoparticles and the effect on their magnetic characteristics, based on irradiation of a sample by the current of spin-polarized electrons. This technique was used to investigate the magnetic properties of nanostructured coatings consisting of iron nanoparticles deposited on a monocrystalline surface of W(001) [11]. The nanoparticles used were in the 20–40 nm size range and height of less than 1 nm. In particular, the study provided the morphological and electronic structures, their dependence on spatial distribution on the substrate and the magnetization vector. In the latter case, the spin-polarized tunneling current was obtained with a tungsten tip covered by a layer of iron.

Further development of these techniques has led to the method of spin-polarized scanning tunneling microscopy (SP-STM), which allows investigation and modification of the magnetic moments of nanostructures. Thus, at sufficiently high densities of the tunneling current, the island consisting of 100 atoms of iron [12] changes its magnetization. In addition, it has been shown that the SP-STM allows the study of reversible magnetization of the island with lateral diameter of about 2 nm, consisting of 40 atoms of iron. In this case the threshold value of the tunneling current is about 1 μA [13]. A continuation of the above studies also considered the effects of magnetic moment rotation of superparamagnetic Co nanoislands due to the tunneling current [14].

Based on the aforementioned studies [12–14] the proposed mechanism of remagnetization of ferromagnetic nanoclusters in the STM includes the heating by the current. Even a small amount of heat, on the order of 1 K (corresponding to 600 nA current), at the sample temperature of 30 K affected the stability of magnetization direction of the small (on the order of several tens of atoms) ferromagnetic island [14]. Thus the typical operating values of spin-polarized tunneling current and the pulse duration were microamperes and hundreds of milliseconds respectively [13]. These values were obtained for particles of about 2 nm size and less than 1 nm in height.

It should be noted that the theory proposed previously [3–5] is based on the following assumption: the total spin momentum of the electrons directed along the magnetization of the ferromagnetic cathode is stored as an integer within the domain. The remagnetization process is described as the result of interaction of two macroscopic magnetic moments – the domain moment and the current moment, i.e. it is assumed that the spin moments of current electrons remain coherent inside the anode.

An alternative approach to the remagnetization description of individual nanoparticles by the current was presented in a previous study [15]. The study considered the remagnetization of ferromagnetic nanoparticles on a non-ferromagnetic substrate in a scanning tunneling microscope (STM) comprised of ferromagnetic tip. The approach is based on the kinetic equations for the number of electron spins directed along and against the direction of magnetization. These numbers are distinct from the equilibrium values when the current flows through a magnetic nanoparticle. It was found that the nanoparticle remagnetization is possible only if the current is greater than a certain critical current I_{cr}.

The value of I_{cr} depends on the size of nanoparticle and the degree of tip and nanoparticle magnetization. And the time of remagnetization tends to infinity, when the current is close to I_{cr}. The estimation of I_{cr} for ferromagnetic nanoparticle of ~ 10 nm size gives a value of about 10 nA [15].

In contrast to previous experiments investigating remagnetization of small ferromagnetic nanoclusters [12–14], the present study is concerned with large nanoparticles ($\sim 15 \times 50 \times 50$ nm^3). A scanning tunneling microscope is employed in which one electrode is the ferromagnetic tip and the other electrode is ferromagnetic nanoparticles on the graphite substrate. The remagnetization of nanoparticles by the electron flow from a ferromagnetic STM tip is investigated. In the first stage the tip is the anode and the magnetization of the tip and nanoparticles coincide. In a subsequent second stage, the process is reversed. With the change of electrical polarity, when the tip represents the cathode, the nanoparticle magnetization is altered as a result of the current flow, and magnetization of the nanoparticle and magnetization of the tip are directed to one side. In addition, the critical currents of remagnetization are measured.

2. Theoretical outlook

According to the theory developed in previous studies [3,4], the total spin angular momentum of electron flow directed along the magnetization of the ferromagnetic cathode is preserved within the domain (i.e. the anode), with a different magnetization direction. In other words, the spin wave functions of the electrons in the flow should also conserve their phases in the domain.

However, only the projections of electron spins along or against the direction of the domain magnetization are conserved in the current. The transverse components of the spins are not conserved due to collisions with other electrons of a ferromagnetic (collision frequency is $10^{13} \div 10^{14}$ s^{-1}). The spins are oscillating with different phases due to incoherent scattering of the different electrons of the current on the domain electrons. Therefore, the resulting transverse component of the spin can be considered equal to zero. The concentrations of electrons with spins along and against domain magnetization as the current passes through nanoparticles are different from their equilibrium values.

The kinetic equations can be written for these concentrations which depend on the input and output flows of electrons with the different spin directions. Assume for simplicity that the magnetization directions in a ferromagnetic electrode (STM tip) and nanoparticles are collinear, i.e. they are directed along or against each other. Let us determine the electron flows from the ferromagnetic electrode to the cathode in the nanoparticle with the directions of spin along (I_+^{ent}) and against (I_-^{ent}) spin polarization in the nanoparticle. At room temperature, the characteristic relaxation time of the energy and moment of an electron which tunnels from one electrode to another and a hole that remains in the first electrode is about 10^{-14}–10^{-13} s.

Tunneling currents which will be considered here are $I \leq 10^{-7}$ A. The average time duration between the passages of the electrons is $\tau_{inter} \geq 10^{-12}$ s. Therefore, the tunneling current flows between the electrodes which are in the equilibrium state.

As was shown in a previous paper [15], if the magnetization directions of the tip and nanoparticles are opposite, then

$$I_+^{ent} = I\frac{\alpha}{\alpha + \alpha_p}, \quad I_-^{ent} = I\frac{\alpha_p}{\alpha + \alpha_p} \tag{1}$$

Here, we have introduced the notations $\alpha = \rho^-/\rho^+$ and $\alpha_p = \rho_p^-/\rho_p^+$, where ρ^-, ρ^+ are the electron densities of states at the Fermi surface with spins against and along polarization in the electrode (STM tip) and ρ_p^-, ρ_p^+ are the same quantities in the nanoparticle. Assuming the dispersion law of D-electrons in ferromagnetic nanoparticles $\varepsilon = p^2/2\,m^*$ (here m^* is effective electron