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Laser induced local modification of magnetic domain in Co/Pt multilayer

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ABSTRACT

Manipulation of magnetic system by the use of laser has drawn the attention of contemporary research. We demonstrate here the modification of magnetic domain in perpendicularly magnetized Co/Pt multilayer by using ultrashort laser pulse. The as-prepared sample shows an out-of-plane saturation magnetic field of 803.4 mT and almost zero remanence with a labyrinth-like domain pattern at room temperature. Atomistic simulation showed that interaction with femto-second laser results in demagnetization of the material in 200 fs followed by a slower recovery. As it indicates a net loss in magnetization, so magnetic force microscopy is carried out to investigate the equilibrium state after the system is relaxed. Demagnetized random domains appeared at the centre of the laser spot with having a rim at the boundary which signifies a deterministic switching with respect to the neighbouring area. Rotation of domains at the central area with the application of small transverse field (100 mT) proves the region to be magnetically weaker. Systematic 3D micromagnetic simulation has been performed to model the laser induced change by selective reduction of anisotropy which is discussed in detail. This shows shrinking of domains to a near circular pattern to minimize the magnetostatic energy. 50% reduction in anisotropy energy is observed with increasing the total energy of the system and a sharp increase in demagnetization energy also takes place simultaneously. This also satisfies the anisotropy in domain rotation with the application of transverse field.

1. Introduction

Nanostructured ferromagnetic films are the key component of hard disks as well as magnetic random access memories. Ferromagnetic materials with high perpendicular magnetic anisotropy (PMA) has become the centre of attraction as it offers high data density. Controlling magnetic order on ultrashort time scale is the main challenge for engineering the future magnetic storage devices which will combine both ultrahigh density storage with ultrafast data processing time. Ultrafast-demagnetization (UFD) opens up a new horizon for magnetic recording, where femtosecond (fs) laser pulses act as an ultrafast stimulus to set the properties of spin ensemble. Since the discovery of the ultrafast process by Beaurepaire et al. [1], the mechanism behind this has been debated. The popular proposed mechanisms are inelastic magnon scattering [2], laser induced spin flips [3,4], relativistic quantum electrodynamic process [5], super-diffusive spin transport [6], change in the domain walls on the sub-pico-second (ps) time scale [7]. Magnetic thin films, having domain structure, have also been studied [8] to investigate the reason behind UFD.

Response of ferromagnetic materials to optical excitations is explained in the light of three temperature model which deals with the co-operative behaviour of electron, phonon and spin, the three heat reservoirs [9]. From excitation to relaxation, it involves a total time scale of few fs to nano-seconds (ns). Sub-ps demagnetization followed by a slower recovery was evident for material systems. The contemporary research in UFD is manifold. One important aspect of it is to study the dependence of magnetization dynamics on material system. I. Radu and colleagues have done a sizable contribution towards the understanding of manipulation of magnetic order on the time-scale of exchange interactions by using x-ray magnetic circular dichroism (XMCD) with atomistic simulation as complementary tool [10]. They focused more on magnetization dynamics of different material systems with ferromagnetically coupled transition metal (TM) alloys and antiferromagnetically coupled rare-earth (RE)-TM alloys [11]. The entire objective is to engineer the future media with tailored dynamic properties. Moreover, experimental and theoretical observation of laser-heat induced magnetization reversal in ferrimagnets [12] and modelling of heat induced switching in synthetic ferrimagnets (antiferromagnetically coupled two TM ferromagnetic materials via a non-magnetic spacer) [13]

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have also been evident. Apart from that, all-optical helicity dependent switching (AO-HDS) has been observed for variety of materials including RE-TM alloys [14] and perpendicularly magnetized multilayer [15].

Apart from the point of view of magnetization dynamics, other important aspect of it is to create anisotropy engineered materials which relates the magnetic property with the structural changes. Kisilewski et al. showed the formation of two branches of out-of-plane (OOP) magnetization state, unlike the reversible thermally induced changes in magnetic materials [16]. Moreover, structural modification with the creation of anisotropy lattice by means of laser interference patterning in Co/Pt multilayer has also been reported [17]. Local probe like magneto optic Kerr effect (MOKE) and microscopic technique along with integral measurements are very much appropriate for this kind of study. The next important point that we want to mention here is magnetic domain imaging which plays a key role to observe microscopic magnetization reversal and nano-scale magneto-structural coupling [18]. With the advent of holographic technique along with XMCD, high resolution domain imaging [19,20] has become possible. Dynamic imaging of domain in response to a fs laser has also been carried out by Schmising et al. [21].

Unlike the referred literature, aiming at magnetization dynamics, here our study describes more about the equilibrium state of a magnetic multilayer (ML) after being excited with ultrashort laser pulse. After getting the structural verification, we have shown here the magnetic domain configuration of perpendicularly magnetized Co/Pt multilayer by means of magnetic force microscopy (MFM) and 3D micromagnetic simulation. The magnetization dynamics for our study is verified by atomistic simulation. We have discussed here the laser affected equilibrium state of magnetic domains and its model with selective reduction of anisotropy for the ML system. The important point to be mentioned here is the use of MFM as a local probe for the system as the laser induced changes are spatially confined around the dimension of the laser spot. On top of that, the domain imaging always specifies the modification of local magnetic properties as domain formation occurs when the gain in magnetostatic energy due to the domain structure is more than the energy required to form the domain wall [22].

2. Experimental detail

The Co/Pt ML films were deposited on Si (100) substrates by DC magnetron sputtering with a base pressure of 1.3×10^{-7} mbar. During deposition, Ar pressure in the chamber was maintained at 1.5×10^{-3} mbar and the substrate was allowed to rotate with a speed of 60 rpm to ensure uniform deposition. The ML has the configuration of Pt (1.3 nm) as buffer layer which is followed by 50 repetitions of Co (1.2 nm)/Pt (0.7 nm) bilayer. Finally, a 2 nm thick Ta layer was grown on top to protect the film from oxidation. The growth rate of Co, Pt and Ta are 0.37 Å/s, 0.283 Å/s and 0.19 Å/s respectively.

The structural characterization of the sample was carried out by x-ray diffraction (XRD). Atomic force microscopy (AFM) provided the value of surface roughness. The magnetic property of the as-prepared sample was examined by superconducting quantum interference device (SQUID) magnetometer and nano-scale domain imaging was performed by MFM with a CoCr coated Antimony doped Si tip.

As the goal of our work is to study laser induced domain modification, so we excited the system with near-infrared laser pulse, derived from a Ti–Sapphire oscillator. The laser pulse was centred at wavelength of 800 nm with a temporal width of 120 fs and a repetition rate of 4 MHz to excite the sample. The beam diameter (full width at half maximum (FWHM)) in the focal plane of a 20 × infinity-corrected microscope objective was determined by a knife edge scan and calculated to be $6.7 \times 7\ \mu m^2$. The power control was achieved by using thin film polarizer with lambda plate. Detail of the experimental arrangement can be found in [23].

3. Structural and magnetic characterization

XRD measurement (as shown in Fig. 1) has been performed for the structural characterization of the as-prepared sample. A main peak is observed at $2\theta = 42.19^\circ$ due to the lattice averaging of Co and Pt and the peak is shifted towards Co peak as the Co content is more with respect to Pt in the ML sample. This suggests the formation of Co/Pt (111) structure and the rocking curve at that position shows a FWHM of 8.4°. Moreover, first order reflection arising from the periodic structure has also been observed as reported by Weller et al. [24]. The surface roughness of the film is measured to be around 4 ($\pm$ 0.2) nm by means of AFM micrograph as shown in Fig. 2(a).

To visualize the microscopic domain pattern, we have done MFM for the as-prepared sample. The correlation of effective anisotropy and stack thickness plays a decisive role for the domain formation in ML. The effective anisotropy is defined as,

$$K_{eff} = K_v + 2 \cdot K_s/t \quad (1)$$

where K_v, K_s are the volume and surface anisotropy constants respectively and t is the thickness of the magnetic layer. Now the increase in Co/Pt stacks will increase the thickness of the Co/Pt multilayer and K_s/t will decrease. But with the increasing thickness, volume also increases, so as K_v. So, in this competition, whenever the interface energy becomes comparable to the volume anisotropy energy, then the system breaks up into domains. Fig. 2 (b) shows a labyrinth-like domain pattern of oppositely magnetized domains for Co/Pt ML. The MFM scan has been done at exactly the same position as in the topography (shown in Fig. 2(a)) with a lift height of 50 nm as it images the stray field emanating from the sample. Line scan over the domains at different locations shows the domain size typically to be 110 ($\pm$ 2) nm. This is also verified by doing two dimensional Fourier transform (2D FFT) of the domain pattern.

Simulation of domain structure in Co/Pt ML has been carried

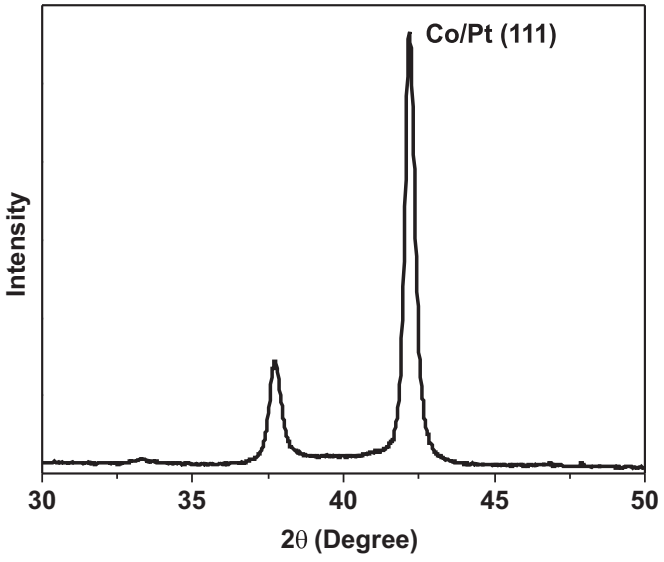

Fig. 1. XRD measurement for Si (*substrate*)/Pt(1.3 nm)/[Co (1.2 nm)/Pt (0.7 nm)]$_{\times 50}$/Ta (2 nm) sample.