Eur. Phys. J. D **43**, 251–253 (2007)
DOI: 10.1140/epjd/e2007-00120-y

THE EUROPEAN PHYSICAL JOURNAL D

Ultrafast spin dynamics of an individual $CoPt_3$ ferromagnetic dot

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Received 9 August 2006 / Received in final form 15 September 2006
Published online 24 May 2007 –

Abstract. We have studied the ultrafast magneto-optical response of $CoPt_3$ ferromagnetic nanodots with diameters ranging from 0.2 to 1 μm. Our experiments combine an accurate temporal resolution using femtosecond laser pulses and a high spatial resolution ($\leqslant$300 nm) obtained with a reflective confocal Kerr microscope. Our experimental approach allows exploring the dynamics of the magnetization of magnetic nanostructures over a broad temporal scale ranging from 100 fs to 1 ns. We report the corresponding relaxation behavior of the electrons and the spins initially excited with a large excess energy above the Fermi level.

PACS. 78.20.Ls Magnetooptical effects – 78.47+p Time-resolved optical spectroscopies and other ultrafast optical measurements in condensed matter – 42.65.Sf Dynamics of nonlinear optical systems; optical instabilities, optical chaos and complexity, and optical spatio-temporal dynamics

1 Introduction

It has been demonstrated that an ultrafast demagnetization of ferromagnetic metals can be induced by femtosecond laser pulses [1–8]. This demagnetization process occurs during the thermalization of the electrons as it was shown recently using 20 fs laser pulses, shorter than the thermalization time of the electrons to a hot Fermi-Dirac distribution [9]. A further partial re-magnetization occurs when the electrons exchange energy with the lattice, a process which depends on the electron-phonon interaction and on the laser pump excitation density. More recently, new studies have demonstrated the potential of time resolved magneto-optical techniques that allow following the magnetization vector in the three directions of space [10] revealing the role played by important parameters such as the magneto-crystalline anisotropy [11].

In this paper, we present an experimental study where we perform femtosecond magneto-optical measurements with a spatial resolution close to the diffraction limit of the light pulses. Toward this goal, we have developed a reflective confocal microscope. Using this microscope and the time resolved pump-probe configuration with femtosecond laser pulses, we have explored the dynamics of individual $CoPt_3$ ferromagnetic dots. This method is essential for the characterization of efficient magnetic devices used for the storage and the processing of information.

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2 Experimental set-up

The laser system consists in an amplified Ti-Sa laser operating at 5 kHz, delivering 150 fs pulses centered at 790 nm. A part of the fundamental beam is used as an intense pump beam that induces the magnetization dynamics. Another part of the laser beam is frequency doubled in a BBO crystal and used as the probe beam at 395 nm. Both beams are focused by an objective lens with a 0.65 numerical aperture. The confocal microscope has been mounted such that one can investigate the individual dots dynamics with a 300 nm spatial resolution for the probe beam and 500 nm for the pump beam, using the polar magneto-optical Kerr configuration. The dynamical signals are detected using a polarization bridge with two photomultipliers and a synchronous detection scheme using a lock-in amplifier (Fig. 1) as a function of the pump-probe delay τ varying from 100 fs up to 1 ns. A static magnetic field is applied perpendicularly to the sample and such that $|H_o| \leqslant 4$ kOe. This detection technique allows us to simultaneously measure the reflectivity and the polar magneto-optical signal. The static and dynamical polar magneto-optical Kerr signals are respectively defined as:

$$Pol_{stat} = (S(H_o) - S(-H_o))/2$$

and

$$\Delta Pol\,(\tau) = [Pol(\tau) - Pol_{stat}]\,/Pol_{stat}$$

where Pol_{stat} refers to the static polar signal without pump. The sample is fixed on a piezo-electric stage with a precision of 2 nm that is moved to scan 80×80 μm images of the array of dots.

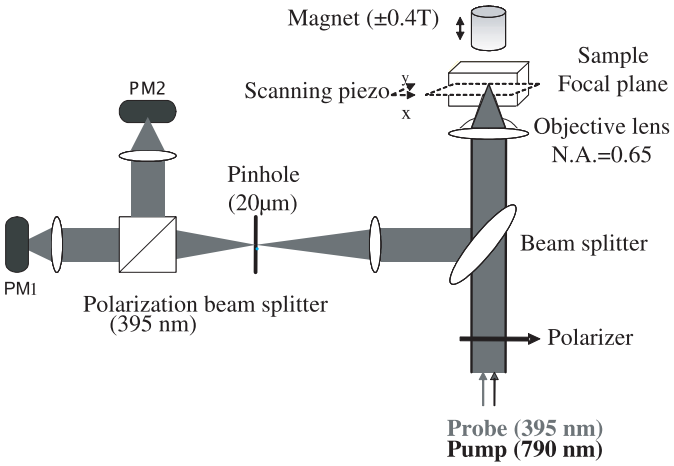

Fig. 1. Sketch of reflective confocal Kerr microscope used for dynamical magneto-optical Kerr measurements.

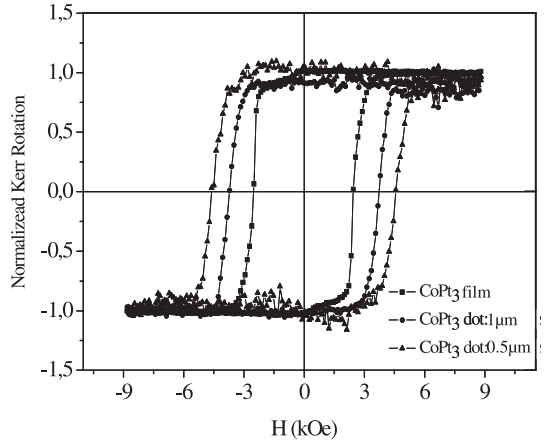

Fig. 2. Polar hysteresis loops for $CoPt_3$ dots and film measured with a continuous fiber laser.

The samples have been elaborated by electronic lithography. They consist in 15 nm thick $CoPt_3$ dots on a Pt buffer layer deposited on a 500 μm oriented sapphire crystal (0001). The diameter of the dots varies from 0.2 to 1 μm. These ferromagnetic dots have a high perpendicular magneto-crystalline anisotropy and a large coercive field. In Figure 2 we have reproduced the hysteresis loops in the polar direction of $CoPt_3$ dots with two different sizes compared to the case of a $CoPt_3$ film. Whereas the magnetization at saturation does not depend on the geometry of the $CoPt_3$ samples, the coercive field strongly increases as the size of the dots decreases. It nearly reaches 4.5 kOe for the 0.5 μm diameter dots. This behavior results from the influence of the shape anisotropy on the static magneto-optical properties. It should also be a crucial factor in the magneto-dynamics since it drastically varies as the electronic temperature increases. Indeed, it has been shown recently that the anisotropy plays a major role on the ultrafast dynamics of ferromagnetic cobalt films [11].

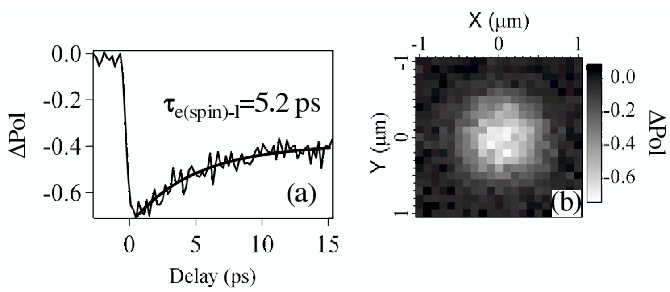

Fig. 3. (a) Femtosecond differential magnetization of a single $CoPt_3$ dot with a 1 μm diameter. (b) Magneto-optical image of the same nanodot for a fixed pump-probe delay at 600 fs. The density of excitation is 8 mJ/cm^2.

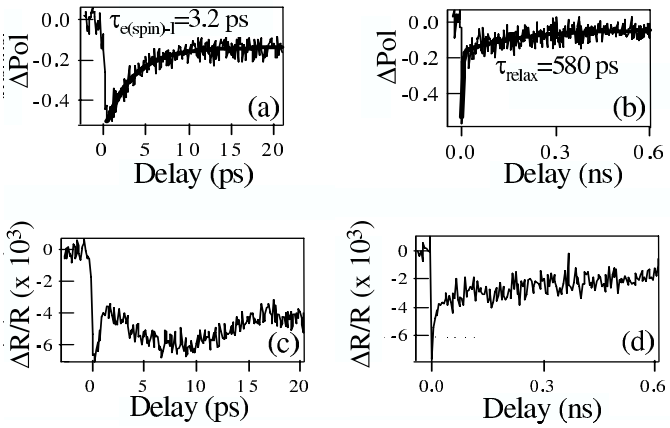

Fig. 4. Time-resolved polar component of the polar magnetization for a $CoPt_3$ dot with 1 μm diameter for short delays (a) and longer delays (b). Corresponding differential reflectivity for short delays (c) and long delays (d). The density of excitation is 6 mJ/cm^2.

3 Ultrafast magneto-optics of single dots

We have performed the magneto-optical dynamics of a single $CoPt_3$ dot with a diameter of 1 μm as shown in Figure 3a for a density of excitation of 8 mJ/cm^2. The signal displays a fast decrease of about 70% in the first hundred of femtoseconds. Following this large demagnetization, associated to a hot electron distribution induced by the pump, there is a partial re-magnetization via the electrons(spins)-phonons relaxation with a characteristic time $\tau_{e(spin)-l} = 5.2$ ps. Let us notice that in this time scale the dynamics of the spins and charges coincide [9]. For each temporal delay, an image of the partially demagnetized dot can be recorded as seen in Figure 3b for $\tau = 600$ fs.

Our set-up allows us to compare the dynamics of the differential polar component of the magnetization at short and long delays (Figs. 4a and 4b) with the one of the differential reflectivity (Figs. 4c and 4d). The density of excitation is 6 mJ/cm^2. As can be seen in Figure 4a after the fast demagnetization, the electrons and spins exchange energy with the lattice with a relaxation time of 3.2 ps leading to a heating of the lattice. This process slows down as the density of excitation increases (compare with Fig. 3a)

due to the increase of the electronic specific heat when the electronic temperature increases. Then, the magnetization slowly recovers with a time constant τ_{relax} of 580 ps when the electrons and the lattice exchange energy with the environment. Let us precise that no precession behavior of the magnetization vector is observed in the configuration adopted here because the external magnetic field is applied along the easy axis perpendicular to the sample plane. This configuration holds the magnetization vector in its initial static direction and therefore no precession can be observed in such specific configuration.

Let us notice that the signals measured are easily interpreted in terms of spins (Figs. 4a and 4b) and electrons (Figs. 4c and 4d) dynamics. They display the characteristic behavior of the electronic dynamics in metals. The initial decrease of the reflectivity corresponds to an increasing of the electronic temperature during the pump pulse duration. The electronic temperature then decreases in two steps. The first one corresponds to the electrons-phonons relaxation with the characteristic time $\tau_{e(spin)-l}$ and the second step is associated to the heat diffusion to the environment with the time constant τ_{relax}. The differential reflectivity signal at short time scale (Fig. 4c) exhibits an oscillation with a 15 ps period which corresponds to an acoustic wave excited perpendicular to the nanostructure.

In conclusion, by combining a high temporal resolution to an accurate spatial precision, our magneto-optical set-up allows us exploring the ultrafast magnetization dynamics of ferromagnetic nanostructures. Potentially, it allows studying the influence of the magneto-crystalline and shape anisotropies as well as pinning effects due to boundary conditions at the edges of the nanostructures. This technological challenge is of great interest not only for studying fundamentals magnetic properties but also for improving performances of magnetic devices used in the storage and processing of information.

This work was supported by the project "Dynamique d'Aimantation de Nano-cristaux Magnétiques Auto-organisés (DANMA)" in the framework of the program PNano 2005 financed by the Agence Nationale de la Recherche in France.

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