Nanoscale Magnetization Dynamics using Ultrashort, Ultra-High-Field Pulses from a Linear Accelerator

This program involves advanced fabrication and characterization of nano structured magnetic thin films and the use of a unique facility at the Stanford Linear Accelerator Center (SLAC) to investigate nanoscale magnetic switching behavior under the influence of high-field, picosecond pulses. The research team consists of Stanford faculty members Joachim Stöhr, Bruce Clemens, Shan Wang, and visiting Professor Hans Christoph Siegmann. The Stanford team in strengthened by close collaborations with Dr. Andreas Scholl from Lawrence Berkeley National Laboratory, Dr. Dieter Weller from Seagate Technologies, and scientists from KOMAG and IBM.

Nanoscale magnetic switching dynamics, although presently poorly understood, is one of the central issues for the magnetic recording industry as the size of the recorded bit shrinks to the nanometer scale and the data retrieval rate increases. We will address this issue by investigating switching in a series of samples with controlled and well characterized magnetic properties including anisotropy, grain size and grain-to-grain coupling. These samples will include advanced recording media, (with magnetic easy axis either parallel or perpendicular to the film), epitaxial nanostructures patterned by electron lithography or focused ion-beam, and nanoparticle arrays formed by chemical synthesis. The switching behavior will be examined by imaging the magnetic structure (using a photoemission electron microscope) before and after high field pulses of varying length in the picosecond range. By applying the field either perpendicular or antiparallel to the initial magnetization we can induce completely different switching mechanisms and address the outstanding questions of magnetic switching.

Introduction and State of the Art

Magnetic information storage technology is rapidly approaching the nanometer scale as storage densities are projected to increase to a terabit per square inch. This presents new challenges and opportunities in nanometer scale materials engineering and in understanding the magnetic properties of nanometer scale magnetic materials. Among the critical issues is the manner and speed which the magnetization direction can be reversed from one stable configuration to another. There are several fundamental physics issues which remain poorly understood, including the role of thermal fluctuations, the basic mechanism of damping of magnetization motion, and the ultimate speed with which magnetization can be reversed. We will address these issues with extension of recent advances in magnetic structure growth, fabrication, and characterization, together with the use of a unique high-field, short-pulse facility.

Ultrashort magnetic field pulses can be generated in solids by letting the relativistic electron bunches generated in the final focus test beam facility (FFTB) at SLAC pass directly through the material, as illustrated in Fig. 1 [1]. The 50 GeV electron bunches carrying currents up to 1000 Amperes are focused to a spot size as small as 1 micrometer. The resulting magnetic field lines are equivalent to those of a straight current carrying wire. At present, the duration of the magnetic field is adjustable in the range from 2-10 picoseconds (ps) by setting the length of the electron bunch. In the future, pulse lengths down to 80 femtoseconds will be available. The magnetic field pulses generated in solid thin films exhibit amplitudes of up to 20 Tesla at distances larger than about 5

microns from the center of impact where the magnetic patterns generated in the material remain entirely undisturbed by the thermal and collisional effects of the electron beam.

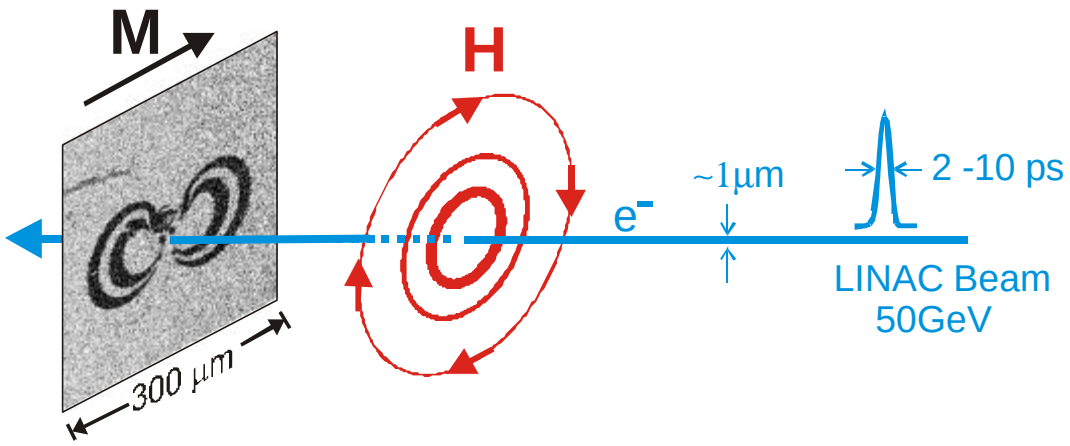

Fig. 1: Principle of the experiment with the SLAC FFTB. The highly relativistic electron bunch generates magnetic field lines in the laboratory frame that are equivalent to the ones from a straight current carrying wire. The magnetic pattern shown in this figure was obtained with a pulse length of 4.4 ps. The pattern was imaged in spin sensitive scanning electron microscopy (Spin-SEM) a long time after the field pulse had been applied. The dark areas indicate the regions where the magnetization has switched to the opposite direction. The sample is a 20 nm thick, epitaxial Co film deposited by magnetron sputtering onto a MgO(110) substrate with appropriate buffer layers.

We will use these unique magnetic field pulses to study magnetization reversal in nanosized magnetic bodies with the overall objective to better understand the dynamics of magnetization reversal. It has already been demonstrated that magnetization reversal can be kicked off with picosecond pulses in thin films and hard magnetic recording media [2]. The precessional mode of reversal that takes place here occurs on the picosecond time scale. It is much faster than the currently employed thermally assisted modes of magnetization reversal which are in the nanosecond (ns) range and which have a time barrier at the nanosecond level given by the necessity to transfer the angular momentum change connected with magnetization reversal to the crystal lattice. Therefore, the magnetic recording community has expressed substantial interest in precessional magnetization reversal fueled also by the recently discovered possibility of generating the required short and strong field pulses through the more practicable spin injection [3]. Therefore, we would like to develop a more complete understanding of precessional magnetization reversal. The three basic questions that we want to answer are:

- To what extent are thermally induced fluctuations of the primary magnetic properties such as the spontaneous magnetization and the magnetic anisotropy important in precessional reversal? This would establish a fundamental limit on the bit size in ultrafast reversal comparable to the one imposed by superparamagnetism on the long term stability of magnetic bits.

- What are the elementary processes allowing the precessing magnetization to relax into the direction of the external magnetic field? In bulk material, the relaxation occurs mostly by the induction of eddy currents. It is also known that the excitation of spinwaves is one relaxation channel in thin films. However, current evidence suggests that there must be more substantial modes of relaxation as well that seem to depend on the strength and/or the

rate of increase of the applied field. To design better magnetic recording heads and media, a complete understanding of the magnetization relaxation is obviously essential.

- Is the coherent rotation model of the magnetization the correct one or are there conditions and circumstances such as encountered in very short and strong magnetic field pulses that the magnetization vector can break up temporarily into smaller units? This is yet another basic question exploring the limits of the applicability of the Landau-Lifshitz equation to describe the dynamics of magnetization processes.

A strength of our proposed program is the coupling of these high-speed, high field magnetic switching investigations with a materials effort to allow investigation of a wide range of nano-engineered materials, including exploratory recording media, patterned epitaxial films and nanoparticle arrays.

Nanostructured Materials

An important element in the proposed research is the nature and the quality of the samples. We will take advantage of the great advances that have recently been made in the fabrication of nanostructured materials. These include films similar to conventional magnetic recording media, i.e. quasi-continuous Co-based thin films, with grain sizes in the 6-15 nm range and some degree of exchange coupling between the grains. We will also investigate dynamics in patterned structures where the coupling between the magnetic particles is completely eliminated and the isolated magnetic grains are on the nanometer size scale. These will be formed with either e-beam lithography using the National Nanofabrication Users Network facilities at Stanford or Cornell, by focused ion beam at IBM, or in assemblies prepared by chemical methods as described in [4] and illustrated in Fig. 2 below.

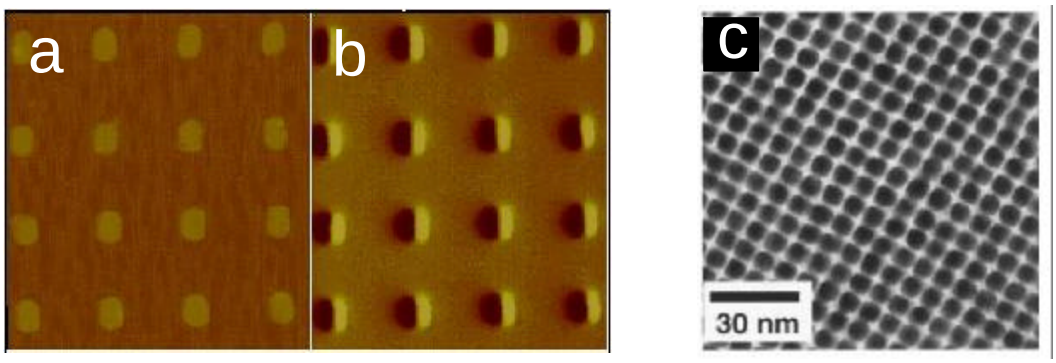

Fig. 2: Topography obtained using atomic force microscopy (a) and magnetic structure from magnetic force microscopy (b) of patterned epitaxial Co film grown on a MgO single crystal substrate. The island size is approximately 330 nm by 130 nm. (c) TEM micrograph of a self assembled superlattice of FePt particles with a particle diameter of 6 nm [4]. Such assemblies have proven to be chemically and mechanically robust. Annealing converts the particles to the high anisotropy fct-phase and transforms them into room temperature nanoscale ferromagnets in which state they can support the high density magnetization
reversal transitions of interest here

Imaging of Magnetic Structure

Of great importance for this research is the imaging of the magnetic patterns generated by the picosecond field pulses at a lateral resolution comparable to the size of the magnetic grains. This will be accomplished by use of X-ray spectromicroscopy to image magnetic structures with high spatial resolution and with element specificity using the **PEEM-2** facility at the Advanced Light Source (ALS) in Berkeley. PEEM spectromicroscopy of ferromagnets is possible by the use of circular dichroism in the threshold excitation of the 2p core hole with the 3d-ferromagnetic elements. This technique, known as x-ray magnetic circular dichroism photoelectron emission microscopy, or XMCD-PEEM, offers high spatial resolution in conjunction with elemental and chemical specificity and surface sensitivity at a sampling depth of typically 2 nm. A third generation instrument is being built with a projected lateral resolution of 2 nm. It is scheduled to be available in one year so that we can expect to work with the improved instrument in this project. PEEM has some unique features of great value here. One is the fact that it can tune in to one specific magnetic element eliminating dilution of the signal from nonmagnetic material as well as the need to work with an atomically clean surface. Another advantage is the possibility to obtain the complete pattern in a parallel measurement, that is in a short time.

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