Introduction to magnetic recording + recording materials

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I will give two lectures about magnetic recording. In the first one, I will present the field of data storage and some of the relevant parameters which have to be discussed when proposing magnetic storage as the relevant technology. In the second lecture I will discuss in more detail the magnetic materials which have been developed (mainly based on transition metals) and some new materials which are being considered for magnetic recording (for example ferromagnetic semiconductors). The physical properties (magnetisation, magnetic anisotropy, spin transport properties …) or physical effects (magnetisation reversal mechanism, magnetic coupling, magnetic biasing, magnetoresistances …) which are relevant to magnetic storage or magnetic sensing will be discussed.

Many families of magnetic materials are relevant to magnetic recording, from hard magnetic materials for storage to soft materials for sensing. From metallic ferromagnets to insulating antiferromagnets, the range of useful materials is quite extended.

Data storage

Information Storage

In our technological age, a huge amount of information needs to be stored in a digital manner. The trend is exponential and shows no signs of calming down. This is the driving force in the field of data storage and makes it a fast evolving industry. Regarding microelectronics, Moore's law is the well known self-replicating trend which predicts that the number of transistors per surface area will double every 18 months. In the last decade the growth of hard disk drive (HDD) bit density has been faster than that of microelectronics and has reached 100% bit density increase per year. A density of 100 Gigabit/in^2, originally thought to be a dream value, has been reached in labs in 2002 and is already in commercial HDD. The new target is 1 Terabit/in^2.
Data storage is a large industry and many technologies compete. The life cycle of technologies is only a few years long and innovation is constant. Before discussing the field of high density magnetic recording, let us detail some of the criteria that govern storage technologies.

Data

The quantity of bits to store is a first parameter. A microprocessor will deal with 32 or 64 bits at a time and a few megabits (Mb) will be stored in cache memory. One hour of music (i.e a CD-ROM) will be equivalent to a few 100 Mbytes (MB) while one hour of video (i.e. a DVD-ROM) will need a few Gbytes of storage. The typical capacity of a personal computer hard disk drive has now reached 100 GB. A small archiving system will deal with terabytes (10^{12} bytes) and a large archiving system will store petabytes (10^{15} bytes). The total capacity of hard disk drives produced per year is already a few exabytes (10^{18} bytes).

Data access

Data should not only be stored but they must also be accessed. Sequential access (e.g. tapes) and random access (e.g. Random Access Memory RAM) are two possibilities, the choices depending on the use. Sequential access is suitable for archiving or to watch a video, whereas accessing files on a hard disk needs random access, as any bit can be required at any moment. The access time and the access rate also matter. The timescale can span orders of magnitude from minutes to access a tape to nanoseconds to read an individual RAM cell and the required data flow can reach Gigabytes per second.

Volatility

Data storage should show a certain lack of volatility. However, non-volatility will be designed taking into consideration the relevant timescale. This can span orders of magnitude, from years in the archiving business down to microseconds in computing.

Competing Physical Effects

Bistable state

A digital memory requires two well defined and stable states to store a bit. Many physical effects offer such configurations. Bits can be stored using two physical levels by mechanically engraving the storage medium : bumps on a CD-ROM or DVD-ROM, tracks on old-age LPs (analogue storage). Optical properties of the media can be modified to create reflecting/non-reflecting bits (recordable (CD-R) and erasable (CD-RW)) or bits with opposite magneto-optical properties (magneto-optical storage). The data can also be materialized by the presence or absence of an electrical charge as in semiconductor memories (SRAM, DRAM, Flash), the presence or absence of electrical polarisation like Ferroelectric RAM (FeRAM), the crystallized or amorphous nature of an alloy as in phase change media (PCRAM memory) and of course the direction of a magnetic moment (magnetic tapes, hard disk media, magnetic RAM).

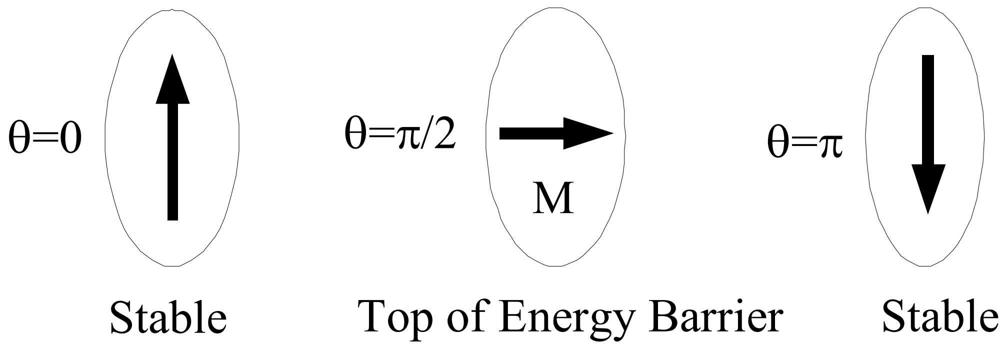
Reading technique

Depending on the way data have been stored and on data density (bit size), the appropriate reading technique is required. Mechanical bits (LPs) were read using a mechanical contact, present CD-ROMs are read using a focused infrared laser reflected from bumps in polycarbonate (bump height is a quarter of the wavelength in polycarbonate) so that the laser beam undergoes destructive interference when reflected from the edge of a bump. Optical bits are also read measuring a reflected laser beam. Electrically stored bits can be read because they control (open or closed) the channel of a transistor, by monitoring the discharge of a capacitor or by sensing the electrical resistance of the bit (phase change RAM). Magnetic bits are read by sensing the magnetic stray field above them or more directly by monitoring changes of the polarization of a laser (magneto-optical effects) or by measuring their resistance (magnetoresistive effect). Unexpected physical effects can be used in innovative systems such as the thermal dissipation change used in IBM's Millipede program.

Characteristics of Magnetic Recording

A ferromagnetic material can possess a well defined axis (the easy-axis) along which its magnetic moments will preferably align. The two possible directions will define two stable states. When the easy-axis is well defined (large remanence of the magnetisation along the easy-axis in the absence of applied field) and if the field necessary to reverse the magnetic moment (the coercive field) is large enough, the material will be called a permanent magnet and can be used to store information. The minimum size of a stable magnetic particle is smaller than 10 nm (depending on the material), which translates directly into high density storage and the intrinsic switching time of a particle magnetisation is in the nanosecond range, which leads to short data read and write times. High density and fast write-time are two of the main advantages of magnetic recording.

Here are some points which will be discussed in the lectures :

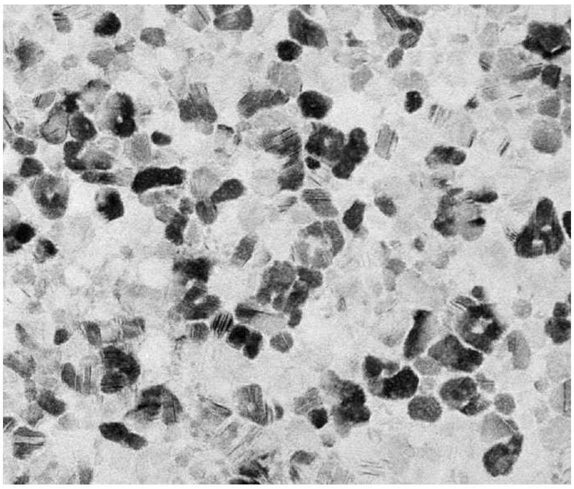


Stable states of the remanence of a magnetic particle. Thermally induced reversal of the particle magnetisation is possible when its volume becomes small enough. This phenomenon is called superparamagnetism and is one of physical limits that is being “pushed back” to improve recording density. Coupling to artifical antiferromagnetic layers has recently allowed the use of particles smaller than the superparamagnetic limit !

45 Gbit/in^2 demo media (Seagate)

•8.5 nm grains

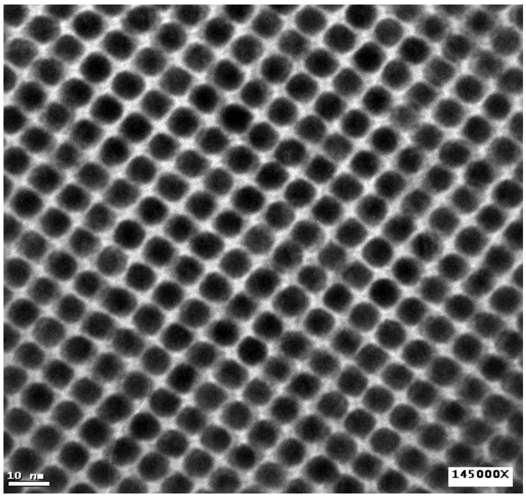
$\sigma_{area} \cong 0.5$



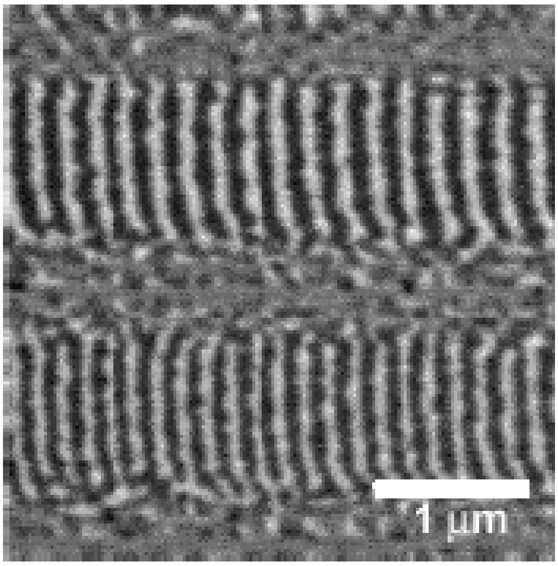
Nanoparticle arrays

•6 nm FePt particles

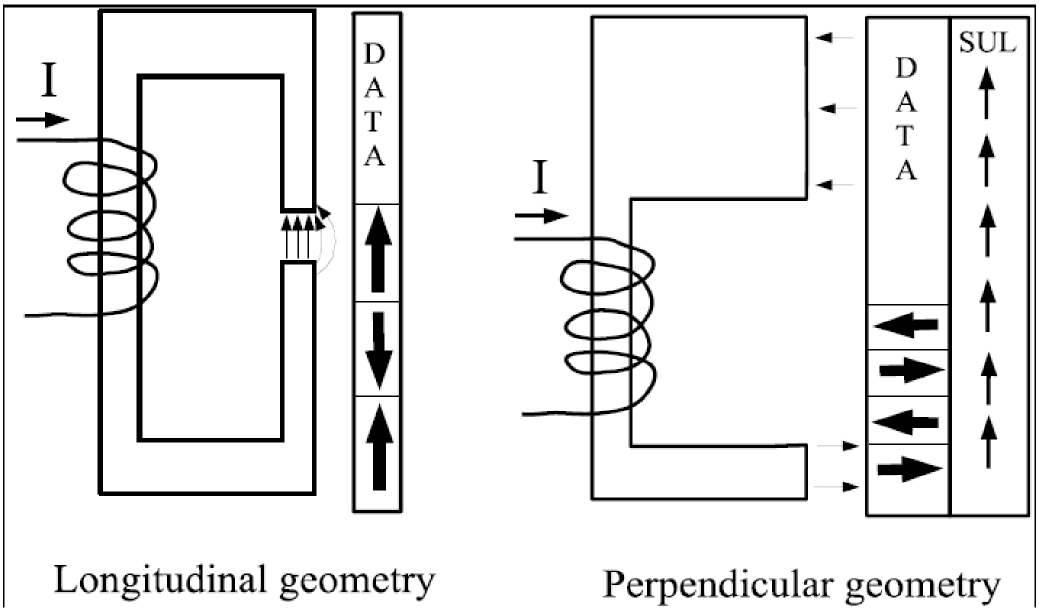
$\forall\ \sigma_{area} \cong 0.1$



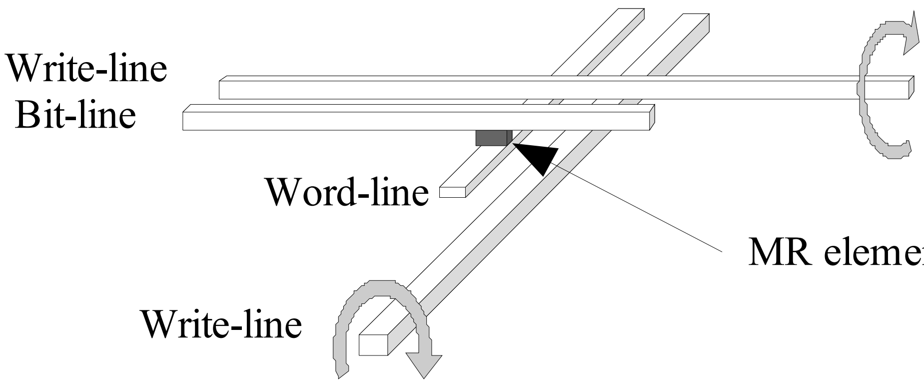
To improve recording density, small particles with very narrow size distribution have to be synthesised. New materials such as high anisotropy FePt $L1_0$ are candidates. The following aim is to spatially organise the particle positions (lithography, self organisation…) and eventually to use only one particle / magnetic bit. (images from D. Weller (Seagate) see S. Sun, C. Murray, D. Weller, L. Folks, A. Moser, Science,287,1989 (2000))



MFM image of recorded tracks (longitudinal recording). One magnetic bit contains roughly 100 magnetic grains (cobalt based) so that the information is stable against losing (i.e. reversing) a few magnetic grains. The way information is coded and physically written gives also possibilities to improve density.



Tapes, floppies and hard disks traditionally used in-plane magnetisation (longitudinal geometry). Since 2006, perpendicular magnetisation is being used in hard disks as a way to improve density. It is a major technological leap, since new media with out of plane anisotropy had to be developed and must include magnetically soft underlayers to guide the magnetic flux. Write heads and read heads had also to be redesigned for this new geometry.



Unit cell of a magnetic RAM. First generation uses magnetic fields to reverse magnetisation. Next generations may use current to assist reversal either by decreasing the coercivity by heating the selected element or even by suppressing the need for write- lines exploiting the spin torque effect. Resistance is modified by the magnetic configuration (this is magnetoresistance). Spin torque is the opposite effect of a spin polarised current on magnetic configuration (including current-induced domain wall motion and even magnetisation reversal in small elements).