Applications : Information storage

Laurent Ranno
Laboratoire Louis Néel, Grenoble, France

A coercive ferromagnetic particle has naturally, at least two remanent states, which is the first step towards storing information. Ferroelectricity or electrostatics may also offer such behaviours but presently magnetism is leading the field of non volatile information storage. To develop such memories, magnetic media have been extensively developped and at the same time a similar drive has pushed forward the reading abilities (space resolution, data rate). Some physical effects such as the anisotropic magnetoresistance (AMR) or the giant magnetoresistance (GMR) have been applied to magnetoresistive sensors or Kerr effect to magneto-optical sensors . This field of physics is closely related to the recording industry, which drives it at a very fast pace. Research in laboratories is hardly ahead of development in the few remaining companies which have survived the race, and nobody knows how a hard disk will look like 10 years from now.
In the first part of the lecture, I will treat the problem of the recording media. Higher densities of storage are required, which means smaller and smaller magnetic entities. Physical limits exist such as superparamagnetism for example. In the second part, I will focus on the writing and reading part of the recording process. A local magnetic field has to be generated and a readable signal has to be extracted from magnetic bits, the smaller the bit, the weaker the signal! The last part of the lecture will deal with prospective devices (MRAM), which should commercially appear in the very near future i.e. 2004 and which may cause a revolution in the field of solid state memories. If so, magnetism would appear in a huge market which is presently entirely based on semiconducting materials.

1 Recording Media

How to store the maximum amount of information in the mimimum amount of space and access it immediatly ? Why magnetism ?

1.1 Particulate Media

In order to store information, the magnetic media use binary coding. For an individual particle this means that two and only two well defined remanent states must exist. The magnetic moment of the particle will keep its magnetic moment in a well defined direction if the anisotropy energy, which defines this easy axis, is strong enough. A uniaxial anisotropy should be developped with an adequate anisotropy field i.e. strong enough to maintain the magnetic moment along the easy axis for 10 years but small enough so that the write head can overcome it to reverse the magnetisation. The first particles used in such a way were elongated ones (needle-like) and the anisotropy energy is due to the shape anisotropy. These first media were particulate media, where the magnetic entity is a particle of iron oxide (Fe_2O_3) or chromium oxide (CrO_2) glued onto a plastic substrate (tape or disk). This is still the type of media used for the low end of the market (basic audio tapes or floppy disks). The anisotropy field $\vec{H}_a$ related to shape anisotropy is the demagnetising field $\vec{H}_d = -N \cdot \vec{M}$, where N is the demagnetising factor. The immediate consequence is that it can not be larger than magnetisation. For an oxide $\mu_0 M$ =0.5 to 1 Tesla. These starting materials are cheap. Producing kilometers of tape is a well controlled industrial process but if 3"5 floppy disks have a constant 1.44 Megabyte format, this is not the case for other storage devices and higher performance media soon became needed. To reduce the particle size keeping a large anisotropy field, one may then switch to magnetocrystalline anisotropy (MCA) as the main source of anisotropy. Grains may have isotropic shape, but now the materials have to be chosen in order to have a strong MCA i.e. no more high symmetry crystalline structure but on the contrary crystal structures with a preferential axis such as the hexagonal structure. Barium and strontium ferrite have such a symmetry and are used also in particulate media. Using these optimised particles, storage density of the order of 100 Mbit/in^2 (surface per bit 6.5 μm^2) can be obtained, but the main use of these large MCA systems is in continuous media.

1.2 Continuous Media

A more elaborate medium is made of a continuous magnetic film. A large MCA material has to be chosen, hexagonal cobalt is the main one. This physically continuous film has to be processed in such a way that it contains magnetically decoupled bits at a small scale (submicron size). Thus the writing head can write a "0" bit anywhere and then switch to a "1" bit keeping the transition region as narrow as possible. This type of medium is used for hard disks or high density tapes. A typical material is CoCr where small cobalt grains (down to 5 nm in size) are separed by a non magnetic chromium rich intergranular phase, which breaks the exchange coupling path. Densities up to 100 Gbit/in^2 can be obtained. Such densities correspond to magnetic grains, which are close to the superparamagnetic limit i.e. when kT the thermal energy is of the order of $\mu_0 M \cdot H_a V$ the anisotropy energy, which prevents the magnetic moment from switching thermally (erasing the information). Tricks, which involve using harder magnetic materials, exchange coupling to antiferromagnetic layers [1] ... are being used to push back the physical limits but another type of media is under development for enhanced performance : patterned media.

1.3 Patterned Media

On a continuous medium, the head cannot aim at one particular magnetic grain. The consequence is that one magnetic bit contains many magnetic grains. A conceptually simple idea to increase storage density is to reduce the magnetic bit to one magnetic grain. A large MCA material such as FePt is a good candidate [2]. The grains would then have to be organised in such a way that they can be addressed easily by the recording head. Patterned media require novel elaboration routes such as e-lithography, nano-imprint, self-organisation + self-assembly ...and would allow the density to progress much farther in the Terabit/in^2 domain.

2 Recording Heads

The recording head has many functions. It has to aim at a specific region on the recording medium. It has to write the information and at a later stage it has to read this information. In former times (1980s) one single head was enough1. The principle was that of an electromagnet. When passing a current in a coil a magnetic field (write field) is created, and when passing the coil above the media, stray fields from the magnetic bits would induce a e.m.f. in the coil. This technique is still used for low performance heads (floppy disk drive, VHS heads). The main drawback of the induction effect $e = -\frac{-d\phi}{dt}$ is that the signal scales as the area of the coil. When the bit size decreases, the coil has to be made smaller to keep the resolution and the signal vanishes.

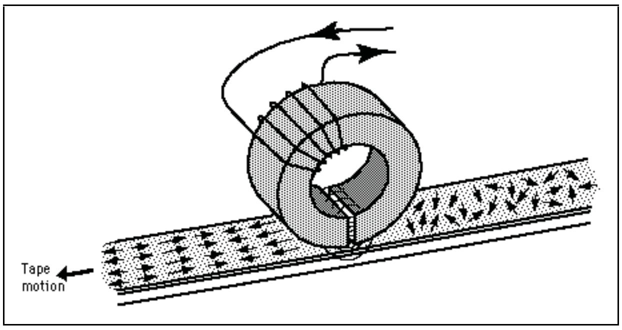

FIG. 1 – Induction based recording

Recent heads (hard disks mainly) are in fact superimposed heads. A coil is still used to generate the field but the read head is based on a magnetoresistive effect. Measuring a resistance produces a signal, which does not scale as the head size. Thus it is possible to keep the signal when decreasing the density. Anisotropic magnetorsistance of a permalloy ($Ni_{80}Fe_{20}$) film or giant magnetoresistance of a trilayer structure gives a few % (AMR) or a few 10% (GMR) variation of the signal when the magnetisation of the free layer follows the stray field and goes away from its reference position.

3 Future of recording

Beyond the limits of the traditional hard disk structure [3], R-D is very active to maintain the increasing rate of storage density. Magnetic media have in-plane magnetisation and perpendicular anisotropy would push back one limit on the bit size (the head must then be completely redesigned for this new geometry). New materials with huge anisotropies may be next in line to push back the superparamgnetic limit but heat assisted writing has to be implemented to reduce the coercive field during writing. Parallel recording on patterned media may also appear one day ...

4 Magnetic RAM

Standart RAM are fast but volatile memories used in all computers. A proposal to introduce magnetic RAM in this field is currently under very intensive development at the moment. Compared to the electrical charge from traditional RAM, a magnetic bit is a non volatile memory, which does not disappear when the the power is off. The intrinsic time to reverse a magnetic bit has already been shown to be much shorter than one nanosecond, whcih makes MRAM potentially as fast as RAM. Severe competition between a few companies (Motorola, IBM, Cypress[4], Infineon, NEC) but also severe competition against ferrolectric RAM (FeRAM) or phase change RAM (PCRAM) make this field difficult to predict but very interesting to follow. Commercial MRAM, FeRAM and PCRAM are supposed to be on the market in 2004. To be followed . . .

Références

[1] E. Fullerton et al. Appl. Phys. Lett. 77 (2000) 3806

[2] S. Sun, C.B. Murray, D. Weller, A. Moser, L. Folks, Science 287, 1989 (2000).

[3] Specifications of Seagate's hard disk drives are at http ://www.seagate.com/

[4] Specifications of Cypress's 256Kb MRAM are at http ://www.cypress.com/