Kalmar ECO-TECH '05 and
The First Kalmar Nanotechnology Workshop
KALMAR, SWEDEN, November 28-30, 2005

NANOMAGNETISM IN INFORMATION STORAGE AND SPIN-ELECTRONICS

Carlo Maria Canali
University of Kalmar, Kalmar

ABSTRACT

The magnetic properties of transition metal nanostructures are very distinct from those of bulk materials. Typically, the magnetic moment per atom is enhanced at surfaces, in ultra-thin magnetic films, and in magnetic nanoparticles and clusters, due to lowered symmetry and reduced coordination at the surface. Similarly, one of the most important properties of magnetic materials, the magnetic anisotropy energy, which characterizes the dependence of energy on collective moment orientation, is considerably altered in systems of reduced dimensionality. F or example, the magnetic anisotropy per atom in two-dimensional (2D) monolayers is more than one order of magnitude larger than in bulk. In one-dimensional (1D) magnetic chains the enhancement is two to three orders of magnitude. It is therefore reasonable to expect that quasi zero-dimensional nanostructures, that is to say ultra-small nanoparticles and nanoclusters, should display even more strongly enhanced anisotropy and other novel magnetic phenomena. Understanding and controlling the unusual behavior of magnetic nanostructures, besides being a problem of fundamental scientific interest, is expected to open the way to important technological applications, some of which are already underway. In this talk, I will present examples of applications of nanomagnetism taken form two different areas: information storage technology and the emerging field of spin nanoelectronics.

In information storage media used in computer hard disk drives (HDD), a thin film made of small magnetic grains is deposited on a surface. The elementary bit of information (0 or 1) is defined by uniformly magnetizing a small region of the film along one of two possible oppositely-directed stable magnetization states. These two magnetization states are separated by an energy barrier equal to the magnetic anisotropy energy of the region. In conventional HDD recording, the magnetization of each magnetic storage cell lies in the plane of the surface. Since transitions between two contiguous bits must be sharp, it is necessary that each bit be made of a large number of magnetic grains, usually between 100 to1000. The present state-of-art HDD, is rapidly approaching the recording density of 50 Gbits/in^2. At this density, the magnetic storage cell size is of the order of 50 nm x 100 nm and the corresponding grain size is below 10 nm. Therefore magnetic storage media involve magnetic nanostructures. One the most challenging problems that need to be addressed when dealing with such small grains, is the phenomenon of super-paramagnetism: because the magnetic anisotropy barrier roughly scales with the grain volume, if the grain is too small its magnetic moment will fluctuate freely between the two bit directions under the effect of thermal activation, rendering non-volatile information storage impossible. At room temperature, this phenomenon takes place for nanograins of size of 10nm. In order to reach storage densities equal or larger than 50 Gbits/in^2, it is this therefore necessary to explore new magnetic materials and especially new magnetic nanostructures which can allow us to by-pass the super-paramagnetic limit. One

interesting possibility is to try to define information bits by using *individual nanoparticles* with unusually high-magnetic anisotropy and a well-defined magnetization orientation perpendicular to the plane of the hard disk. As an attempt in this direction, we have undertaken a theoretical study of the magnetic properties of two-monolayer thick Co nanoplatelets with an equilateral triangular shape of a few nanometers in size [1]. Experiments carried out at the University of Texas at Austin that partly motivated our work, have shown that these flat magnetic nanostructures display a magnetization perpendicular to the Silicon surface on which they are built, and a magnetic anisotropy energy approximately one order of magnitude larger than the bulk value [2]. The high anisotropy energy of the Co nanoplatelets combined with the Si-substrate surface, provides a material that seems ideal for logical circuits integrated with ultra-high-density memory. Our theoretical analysis is carried out using a microscopic quantum model, designed to realistically capture the salient magnetic features of large nanoclusters containing up to 350 atoms. Two different truncations of the FCC lattice are studied, in which the nanoplatelet surface is aligned parallel to the FCC (111) and (001) crystal planes respectively. We find that the higher coordination number in the (111) truncated crystal is more likely to reproduce the perpendicular easy direction found in experiment. In some regions of the parameter space that define our model, we find that, in agreement with experiment, the axis of magnetization is perpendicular to the surface, and the value of the magnetic anisotropy energy per atom is anomalously large. The possible role of hybridization with substrate surface states in the experimental systems will be discussed.

In the second part of my talk I will describe a new class of nano-electronics devices based on magnetic nanostructures. In these systems, the spin of the electron, besides its electric charge, plays a crucial role in the functionality of the device, adding a completely new dimension to information transfer that conventional electronics industry has neglected for more than sixty year. Specifically, I will discuss an example of a magnetic single-electron transistor developed together with my collaborators at Lund University [3]. The device, shown in the figure, is fabricated by atomic force microscopy (AFM) and consists of two ferromagnetic Ni electrodes acting as a source and a drain, and a third electrode acting as a capacitor gate. All electrodes have are 30 nm thick and approximately 100 nm in size.

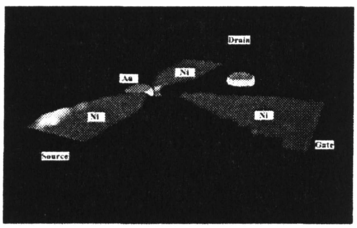

Figure 1. AFM image of a magnetic single-electron transistor.

Using AFM with a specially designed software, a non-magnetic Au disk of radius equal 30 nm is positioned into the gap between the drain and source electrodes. Electric current in this nano-device flows through quantum mechanical tunneling of the individual electrons from and to the electrodes into and out of the central island. Because the central island is so small, the IV curves of the device are highly non-linear and can be controlled by means of the bias voltage between source and drain, and the gate electrode. The novelty of the device is due to the fact that the electrodes are magnetized. We find that electric current depends sensitively on the applied magnetic field. In particular, if we define the magneto-resistance as the ratio [I(B = 0) – I(B = 0.1 T)] / I(B = 0), where I(B) is the current measured at a given external magnetic field B, we find that the magneto-resistance displays oscillations with a quasi-periodic sign change as a function of the bias voltage.

A theoretical analysis shows that crucial in the understanding of this behavior is the fact the current through the device depends on the relative orientation of the magnetization of the external electrodes: the electric resistance is enhanced if the two magnetization directions are opposite and is decreased if the two orientations are parallel. Thus, a magnetic single-electron transistor acts like a giant-magneto resistance effect sensor, now commonly used in the read heads of HDDs. The important fact is that the dimensions of our device are of the order of 100 nm. In principle, spin-electronic devices of this size could be employed as read heads for individual magnetic bits of nanometer size.

ACKNOWLEDGMENTS

This work is done in collaboration with my students O. Strandberg and L.Michalak at the University of Kalmar, A.H. MacDonald at the University of Texas at Austin (USA), and Ruisheng Liu, H. Pettersson, and L. Samuelson at the Nanometer Consortium of Lund University.

REFERENCES

[1] Strandberg, O. T., Canali, C. M., MacDonald, A.H., 2005. Magnetic Anisotropy of Isolated Cobalt Nanoplatelets. Submitted to Physical Review B.
[2] Ming-Hu Pan et al., 2005. Quantum growth of magnetic nanoplatelets of Co on Si with high blocking temperature, *Nano Letters* 5, 87-90.
[3] Liu, R., Michalak, L., Pettersson, H., Canali, C. M., Samuelson, L., 2005. Spin-dependent transport in ferromagnetic single-electron transistors. Presented at the international conference Spintronics'05, Poznan, Poland, September 2005.