6 Magnetic Memories

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Magnetic tape recording predates modern physics. In 1898, according to my 1963 Encyclopedia Brittanica,Valdemar Poulsen applied for a Danish patent on magnetic tape, and was involved in manufacturing and marketing devices based on it. The tapes were made in much the same way that they were made recently, by embedding small magnetic grains in a flexible emulsion on a strong backing. This venture was not commercially successful, and the technology took off a quarter of a century later, when talkies took over from silent movies. Text was still being encoded digitally on punched paper tape or on punched cards in the 1980s, but by that time the computer industry was driving magnetic recording to steadily increasing density of information, speed of access and recording, and reduction of cost. Electronic storage was possible at high density and low cost, but electronic storage required active devices with a power supply. Static devices were needed to store data in the absence of a steady and reliable power supply, and magnetic recording looked like the best candidate for such data storage.

Digital recording is obviously preferable to analog recording, because a digital record can be checked for degradation of the record from the desired $\pm$ format, and corrected to the desired form, whereas an analog device has a continuous range of acceptable values, so it is not obvious how to correct it if the values drift. In ferromagnetic materials, like Fe_2O_3 or CrO_2, fabricated in such a way that the individual crystals are much longer in one direction than they are in the perpendicular directions, the magnetization will be aligned with the long direction, and so each crystal has two possible equilibrium directions, with a high energy barrier between them. Such crystals make good analog devices, since there is high energy barrier separating the two directions of magnetization, but there are problems with reducing the size too far and retaining the stability. One important issue is that if the magnetized regions are too close to one another, parallel regions alongside one another tend to demagnetize one another. Antiparallel regions stabilize one another. In digital records the magnetic regions, each containing many magnetic grains, can be made long and narrow, and be spatially separated from one another, so that demagnetizing fields are reduced and stability is increased. Each of these regions represent one bit of data.

The traditional way of reading magnetic tape, or its successors such as magnetic disk, was to use an induction coil. According to Faraday's Law, if the magnetic field through a loop of wire changes, a voltage will be induced in the loop, which can generate a current round the loop. If instead of using a single loop you have a coil of wire wound N times in the came direction, a voltage N times as large is induced, and this induced current, going in one direction when the field increases, and in the opposite direction when it decreases, can be used to measure the magnitude and direction of the field. If the magnetized regions are too close together, the magnetic fields due to neighboring regions overlap, and so they are hard to read.

It was found to be more satisfactory to use *magnetoresistance* to read the direction of the magnetization, which IBM started using around 1991, according to Grünberg's 2007 Nobel lecture. In a magnetic metal such as iron electrical resistance depends on whether the current is flowing parallel and antiparallel to the direction of magnetization. In most materials this difference in resistance at room temperature is only a fraction of a percent of the average resistance, but in 1984 it was discovered how to make materials with a very large difference in the resistance in the two directions. This led to the award of the 2007 Nobel Prize in Physics to Albert Fert and Peter Grünberg for their parallel work.

6.1 Magnetoresistance and memory heads

Usually a magnetic disk is magnetized in a direction parallel to the surface, although the possibility has been raised of increasing the storage density by magnetizing perpendicular to the surface, according to a 2000 article on Directions in Information Technology (Thompson DA, Best JS, IBM J. Res. Devel. **44**, 2000, 311-322). The basic magnetoresistance head consists of a nickel–iron strip attached to two contacts. A current is passed between the two contacts along the magnetoresistive strip, and a reading of the voltage gives a reading of the magnetization of the element of the disk (a single bit) immediately under the head.

There is an excellent account of the background and importance of the 2007 Nobel Prize awards in the December 2007 issue of Physics today, which I have put up on the class website. There are slides of their presentations available on the Nobel Prize website; the first part of Grünberg's presentation gives the basic physics and the results of the key experiments, while the second half concentrates on the applications. The basic discovery was that the small magnetoresistance of iron could be greatly enhanced by incorporating it in a sandwich. Both Grünberg and Fert studied the effect of interleaving layers of ferromagnetic iron with layers of antiferromagnetic chromium. The first IBM magnetoresistance read-head on the market was 4.5 μm across, and the disks had an information density of 1.1 gigabytes per square millimeter. In the next six years the information density was increased by a factor of 30, and then giant magnetoresistance read-heads were introduced in 1997, and in the next eight years the width of the head was reduced to 120 nm, and the density of information on the disk was increased by another factor of 70, so that the density of information scales more or less as the square of the width of the read-head.

These sensitive detectors of magnetization can be used for many other purposes, which are outlined in Grünberg's presentation.