Magnetic Data Storage and Nanoparticles

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Introduction

Magnetic storage, specifically in hard drives has advanced significantly since the first disk drive built in 1956 [1]. Interestingly enough, most of the changes thus far have been realized by scaling the components of a disk drive [1]. In recent years, the superparamagnetic limit has been seen as a possible limit to the rapid increase in hard drive capacities. Antiferromagnetically coupled (AFC) magnetic media layers appear as if they have given some breathing room for the next few years. Once the limits of the AFC technology are reached, nanoparticles may be the next technological step in linear magnetic data storage.

Background

The first hard drive was built by IBM and was used in RAMAC (Random Access Method of Accounting and Control). The RAMAC hard drive was huge, being housed in a casing the size of a refrigerator. The actual magnetic storage was done on 50 aluminum platters, stacked vertically. These platters were coated with paint, similar to that used on the Golden Gate Bridge, except that powdered iron oxide had been mixed into it [1]. The use of oxide technology has continued for many years, and can be see in older hard drives. The characteristic light brown color of the platters is a result of the oxide [2]. Each platter was two feet in diameter [1].

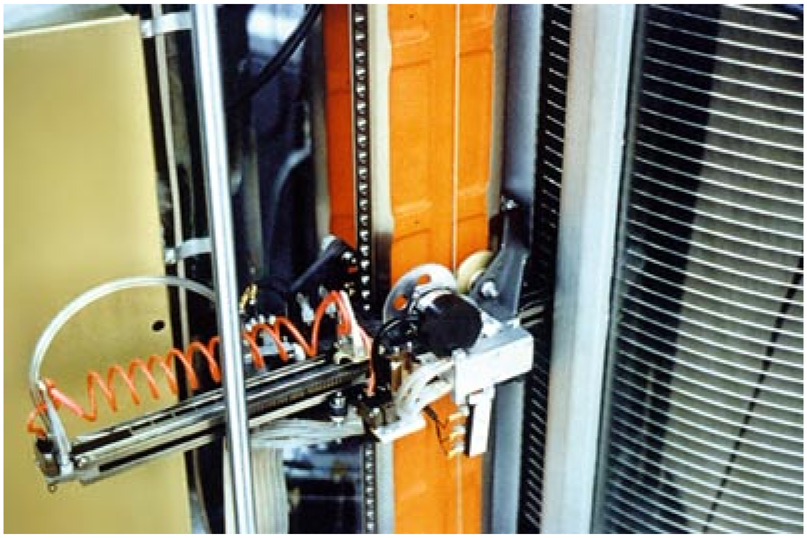


Figure 1 First computer disk drive built by IBM in 1956 as part of RAMAC. On the right side of the image, some of the 50 platters are seen. In the center of the image is a pneumatically controlled access mechanism. [1]

Magnetic storage works by having a read head detect changes in polarity of magnetic media. Rather than having positive and negative polarities representing the binary 0s and 1s, 1s are represented by changes in polarity while 0s are represented by the lack of a change in polarity [1]. As stated earlier, the vast majority of increases in storage capacity (Figure 2) have been the result of scaling of the components. A good example of this scaling would be in the read/write heads of hard drives. The RAMAC's heads were 25 micrometers above the platters, levitated by a layer of compressed air [1]. Disks after the RAMAC have instead used the aerodynamics caused by the rotation speed of the platter to suspend the head a mere 15 to 20 nanometers above the platters [1].

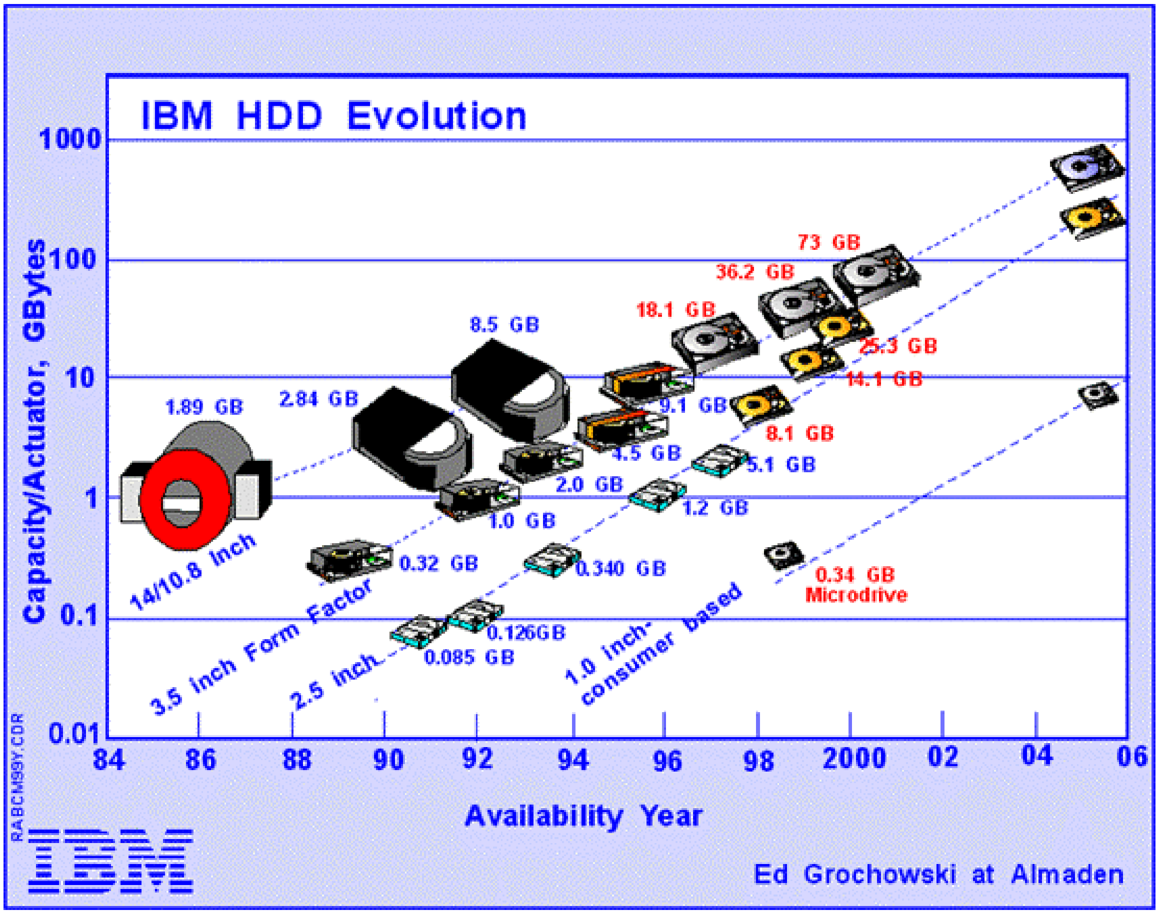
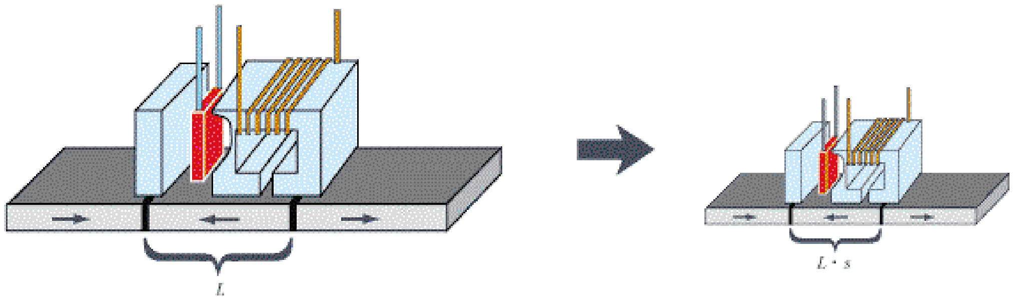


Figure 2 Evolution of IBM hard disks over the past 15 years [3] Note the decreasing form factors from 14" to 1.0" as one moves from 1984 to the present.

A more direct illustration of this scaling is shown in figure 3. The interesting thing about scaling though is that a linear scaling by a factor of s, results in area density increases by a factor of s^2 [4].



- Shrink everything, including tolerances, by scale factor *s* (Requires improved processes)
- Recording system operates at higher areal density $(1/s)^2$ (Requires improved disk, head, and electronics materials and designs)
- Signal-to-noise ratio decreases

Figure 3 Basic scaling for magnetic recording [4]

This scaling runs into limits though as the paramagnetic limit is approached. In simple terms the paramagnetic limit is reached as the magnetic energy stored becomes close to the thermal energy of the atoms, making it impossible to store magnetic states [3,4,5]. The relationship between the magnetic energy density per particle (K_uV, where K_u is the magnetic anisotropy energy density, and V is the grain volume) and the thermal energy (k_BT, where k_b is Boltzmann's constant, and T is temperature in Kelvin) needs to exceed 40 for stability for great than 10 years [5].

Analyzing the relationship K_uV/ k_BT, one can quickly see that while Boltzmann's constant is fixed, as is the operating temperature for all intents and purposes, the magnetic anisotropy energy density and the volume can both be increased. The problem arises though that the volume must be decreased to increase storage capacity of hard drives, unless one wants hard drives that are as big as the original RAMAC drive. Therefore, to maintain a K_uV/ k_BT ratio greater than 40, the magnetic anisotropy energy density must be increased. The problem with increasing K_u is that the critical coercive field, H_{CR} scales linearly with K_u [5]. This increase in H_{CR} means that the energy required to write to the disk increases, as it takes more to reverse the fields in each grain.

The method currently being used to combat this superparamagnetic limit is antiferromagnetically coupled (AFC) magnetic media[6]. The initial work that lead to the commercialization of AFC technology was done by Parkin and colleagues at IBM [7]. It was found that in a superlattice formed by Co/Ru, the "saturation field and saturation magnetoresistance are closely related and that their magnitude oscillates as a function of t_{Ru}." [7] By taking advantage of this effect, the magnetic thickness (Mrt, product of Mr, the magnetic moment density and t, thickness) can be reduced, allowing for transitions to be more closely packed [6]. Previously, the main way to reduce Mrt was to reduce the thickness of the layer, but as this lead to decreases in volume, K_uV would decrease, and the superparamagnetic limit would be approached. By using AFC media, it is found that

$$Mrt_{eff} = Mrt_{top} - Mrt_{bottom}$$ [6]

By reducing the Mrt in standard magnetic media, the pulse width is reduced, which allows for higher signal to noise ratios in the transition regions [5]. It has been found that this trend also holds true for AFC media, with AFC media behaving similarly to single layered magnetic media [5].

A schematic illustration of AFC media is shown in figure 4.

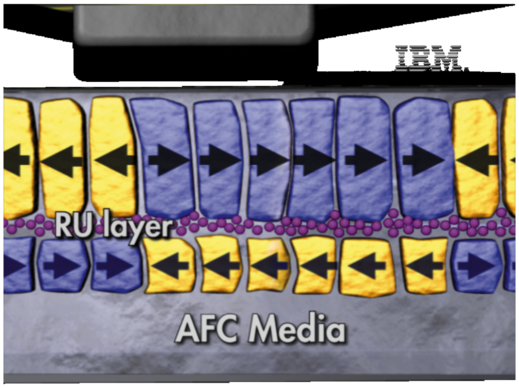


Figure 4 Schematic illustration of AFC with single magnetic transition [8]

The commercialization of AFC media has been most clearly illustrated by IBM's and Fujitsu's use of ruthenium, a metal similar to platinum, between standard layers of magnetic media, resulting in values of Mrt that are independent from the actual thickness. Even though the Ru layer used is only 3 atomic layers thick, nanoparticles are not used, but instead, normal sputtering methods are employed [9].

Use of Nanoparticles

Currently, multiple grains are used to store each bit of information, and it is estimated a ten-fold increase in capacity could be achieved if this could be reduced to one grain per bit [4]. One way to achieve this would be using a nanocrystal superlattice structure formed from FePt nanoparticles [10]. It has been found that FePt alloys have large K_u values, approximately $7 * 10^6$ J/m^3 [10]. By reducing $Pt(acac)_2$ (acac = acetylacetone) and decomposing $Fe(CO)_5$ in high temperature solutions in the presence of oleic acid and oleyl amine, monodisperse nanoparticles were prepared. Particles formed were about 3nm, and could be increased up to 10 nm by adding more reagents at a controlled rate. Centrifugation after addition of flocculent allowed for further isolation of particles of specific sizes [10].

By forming a thin file of the colloid, consisting of the FePt nanoparticles and floculents such as ethanol, and then allowing the solvent to evaporate slowly, a superlattice can be formed. Studies of these superlattices showed that the standard deviation of the particle size was less than 5% in diameter (Figure 5).

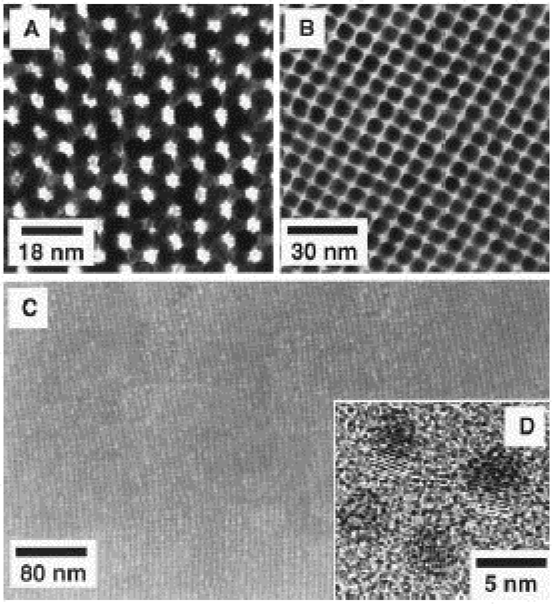


Figure 5 (A) TEM micrograph of 3D superlattice with 6-nm as synthesized particles (B) TEM micrograph of a 3D assembly of 6-nm $Fe_{50}Pt_{50}$ sample after replacing oleic acid/oleyl aminie with hexanoic acide/hexylamine (C) HRSEM image of a ~180 nm-thick, 4-nm $Fe_{52}Pt_{48}$ nanocrystal assembly annealed at 560°C for 30 minutes under 1 atm of N_2 gas (D) High resolution TEM images of $Fe_{52}Pt_{48}$ nanocrystals annealed at 560°C for 30 minutes on a SiO coated copper grid [10]

The annealing of these samples results in transitions from FCC to FCT structures [10]. The resultant FCT FePt superlattice structure has magnetic properties, such as K_uV/ k_BT =48 for nanoparticles of 4 nm diameter, implying that they could be used for magnetic storage media [10]. Some predictions indicate that this could result in areal densities in the terabits per square inch range [2,10].

Further work with this has shown that the size, within one atomic layer, composition, shape, internal structure, and surface chemistry of nanoparticles can all be engineered, and then used to form superlattices with specific properties [11]. A schematic illustration of the process used is shown in figure 6.

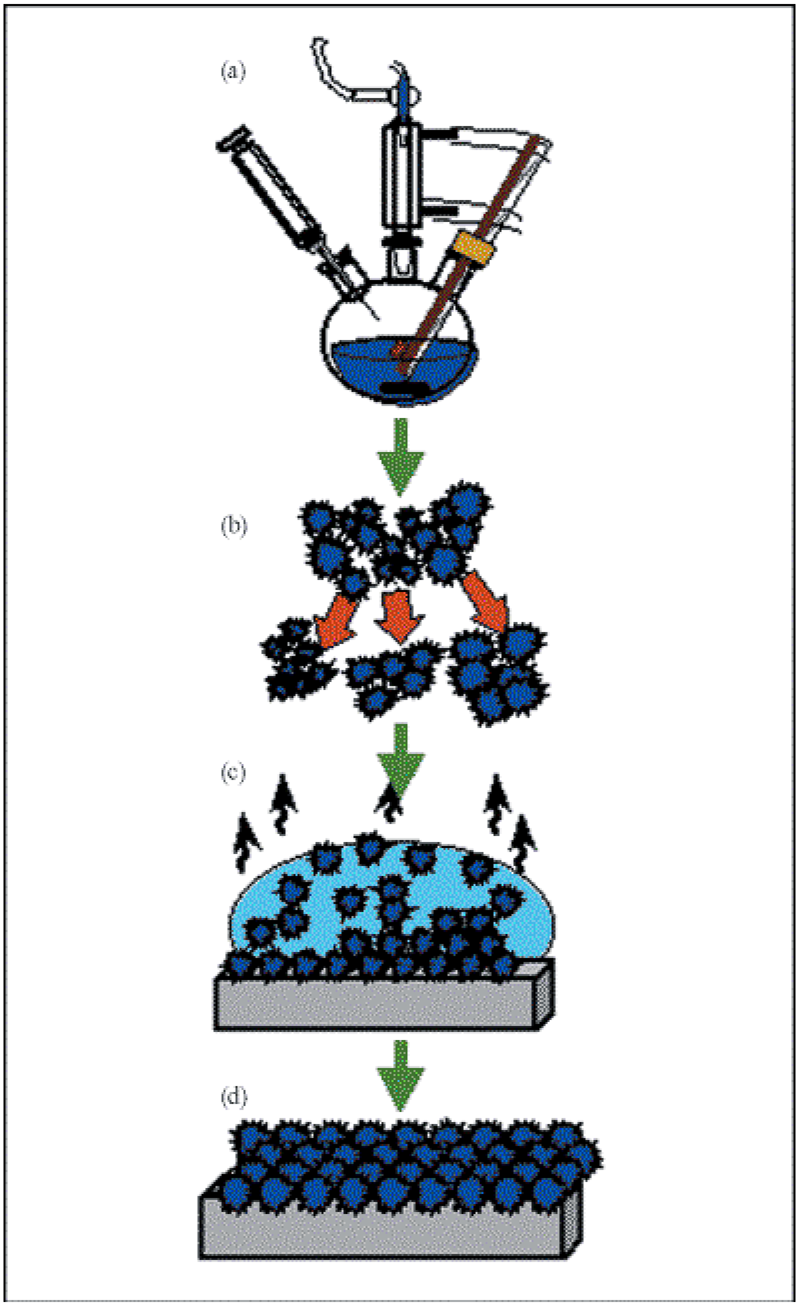


Figure 6 Schematic representation of the synthetic procedures to (a) synthesize nanocrystal samples by high-temperature solution-phase routes, (b) narrow the nanocrystal sample size distribution by size-selective precipitation, (c) deposit NC dispersions that self-assemble, and (d) form ordered superlattices [11]

Two methods of preparing monodisperse (<10% standard deviation in size) nanocrystals are described by Murray et al. Both methods involve a short nucleation stage, followed by a controlled growth stage [11].

The first method involves adding reagents rapidly into a hot solvent, causing a supersaturated solution to form. Nucleation occurs to combat this supersaturation, resulting in the concentration dropping below the critical concentration for nucleation.

The second approach described involves the mixing of the reagents at low temperature, where there is not enough energy to start a reaction. By slowly heating the solution, the solution becomes supersaturated, and again, nucleation occurs to relieve the supersaturation. Careful control of the temperature can limit the nucleation to a one time event [11].

Both approaches rely upon extremely fast nucleation periods to limit the size distribution of the nanoparticles [11].

By controlling the parameters of time, temperature, concentration, and chemistry of reagents and surfactants, monodisperse nanocrystals were formed. Further controls are also mentioned, such as:

- Using two surfactants, one that binds tightly and on that binds less tightly. The surfactants that tightly bind limit growth while the ones that bind less tightly permit rapid growth. By applying carboxylic acid and alyklphosphine stabilizers liberally, the size of Co nanocrystals was tightly controlled [11]
- Controlled addition of reagents after the nucleation phase to get larger particles [1]

It should be noted that the synthesis procedures resulted in diameters with less than 10% standard deviation, and then size-selective precipitation resulted in standard deviations less than 5%.

Conclusion

While nanoparticles are not currently used in magnetic storage media today, research is being carried out in the use of nanoparticles and their use to form superlattices. This will allow for the reduction of the size of a bit cell from multiple grains to single particles [10,11] and could result in dramatic increases in areal density [4]. Current limiting factors involve the lack of read and write heads that could work with such small bit cells [4].

References

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