INNOVATIVE MASS STORAGE TECHNOLOGIES

IMST

WHITE BOOK

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INNOVATIVE MASS STORAGE TECHNOLOGIES

“IMST White Book”

Mass data storage, memories for the future everyday life

A road map for the European R&D

The authors are currently active in the area of Mass Data Storage Technologies in the Industry, the Universities or the Research Centres from the European Union. They represent the scientific committee of the Innovative Mass Storage Technologies Conference (IMST). Created in 2000 by European scientists and industrials, this International Conference provides a unique opportunity to cover the latest advancements of the research and to observe the latest trends in the areas of solid state, optical, magnetic and emerging technologies for data storage.

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The .pdf file of the Innovative Mass Storage Technologies White Book report can be downloaded on the Web site of the IMST Conference : http://www.ex.ac.uk/IMST2002

1. Contents

A two page summary (**Part. 2**) first underlines the key role of Mass Data Storage in the Information and Communication Society and the proposed actions to strengthen the European position.

Part 3 offers a large overview of the impact of Mass Data Storage on industry, economy and citizen life, and displays some of the most exciting opportunities opened in the near future.

Next, **part 4** provides a thorough review of the technical trends, of the economic activity (with an incentive on the European position), in the four areas covered by the White Book: Solid State Memories, Optical Memories, Magnetic Storage and Emerging Technologies for Memories. In each case, the state of the European research is reviewed, and the authors underline what they consider the best actions to maintain and develop a strong EU based research and industry.

Part 5 is brief, but dedicated to a real challenge: how we will be able to transmit to the future the huge amount of data we create, using technologies that are so rapidly evolving (and for some disappearing).

Part 6 suggests actions to ensure the development and exploitation of appropriate R&D in Mass Data Storage Technologies in Europe

Finally, **Part 7** reminds of the past EU sponsored research effort in Mass Data Storage by providing a list of recent or ongoing research projects.

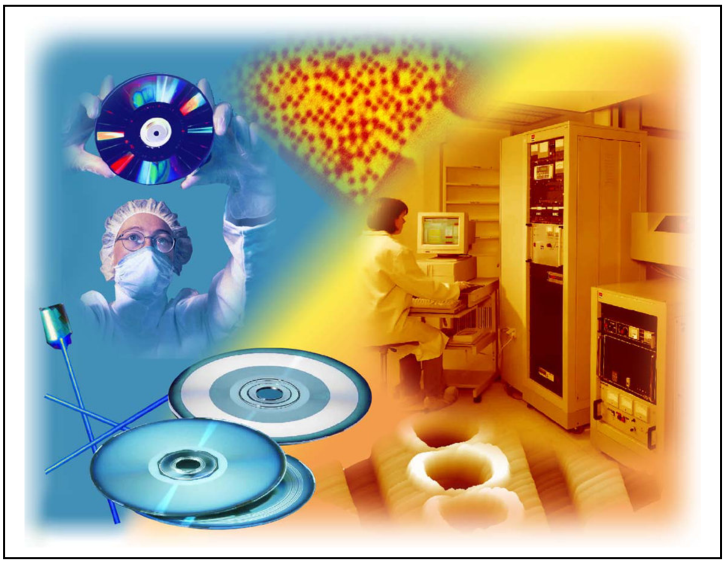


Image taken from the IMST Conference graphic files

2 Summary

At the core of the development of the ICT technologies over 40 years has been the continuous and fast increase of the capacity of memories. Incredible progress in magnetic storage (hard disk…), optical formats (CD, DVD…), and semiconductor solid state memories (USB keys…) has been enabled by innovation from intensive R&D in Europe, US and Japan, and fostered innovation in many other areas of technology.

The progress in mass data storage is intimately associated with the development or the creation of key areas of the modern economies, such as telecommunications, leisure (music, films, games…), banking, improving work productivity and work accessibility (easiness), security and health… World-wide, **mass data storage technologies are a market in the 40 – 50 Billion Euros range. Europe has been and is a global driver in many areas of storage research and innovation through a strong supply industry.** Currently, around 70,000 people in Europe are directly involved in research, development and manufacturing related to mass data storage (and many more indirectly).

To preserve the existence of EU based world-class production facilities in this area, and to secure competitive positions in the markets linked to the emerging technologies for mass data storage, it is crucial that a favourable environment for innovation and investment is created. This is especially true for small and medium sized enterprises (SMEs), that play an important role in an area driven by a fast innovation rate. All care should be taken to ensure that **the favourable basis provided by the European excellence in R&D can be maintained and translated steadily into commercially viable processes, products and economic activities.**

This paper reviews the state of the art in research on the current and emerging technologies for mass data storage, the market trends and the European position in research and industry. It proposes actions as part of an integrated approach to maintain and strengthen European R&D and industry in the field of mass data storage technologies. It considers the most important issues to ensure the creation and exploitation of R&D for the benefit of society:

- to increase investment and coordination of R&D for new technologies for mass data storage, including hardware, and complex systems using different technological know-how;

- to support the interdisciplinary education and training of research personnel, taking care to promote a stronger entrepreneurial mindset;
- to cluster joint projects including the new EU member countries and promote international collaboration, when needed beyond Europe;
- to support assessment activities to ensure that European R&D excellence is translated into wealth-generating products and processes;

Specific recommendations are described at the end, which are in agreement with the conclusions of the European Councils of Lisbon 2000, declaring the commitment to develop a dynamic knowledge-based economy and society, of Gothenburg 2001, aiming at sustainable development, and of Barcelona 2002, targeting 3% of GDP funding for research.

3 Mass data storage technologies in IST: challenges and opportunities, the European position

3.1 Information and Communication Technologies today: an area of opportunities, a major source of economic growth

During the last 15 years, ICTs have provided a number of radically new devices / technotoys that have improved the daily life of the EU citizen: mobile phone, digital camera, MP3 players, PC, PDA, credit cards, video on discs, flat screen, HD TV, fast communications (ADSL), home and work security (wired or wireless), automatisms (doors, shutters..), improved methods for production and increases in productivity… Most have been made possible by **combining the progresses in silicon technologies**, CAD, simulations, architecture design, and **a mass storage component with new capabilities**. Strikingly, the time to market (and citizen) of these new technologies proved far more rapid than for the previous ones (automobile, telephone, television…). The roots of such an evolution can be found in the combination of two highly favourable factors: the new ICT technologies fulfil real expectations and needs of the citizens, and they are also affordable and accessible to a large majority of the consumers.

The economies of Europe, US and Japan hugely benefited from the rapid growth of the Information Technologies, that has been made possible by strong investments in R&D, both by companies and by states (or Europe) or state sponsored institutions.

"We begin the 21st century with a general expectation that the one-two punch of science and technology will, by itself, generate an unending .flow of discoveries, tools and gadgets to bring us closer to a utopian future. This premise has also shaped a general understanding of innovation as equivalent to discovery, invention and the flow of new technotoys. In reality, invention has always been as distinct from innovation as rivers are from oceans: one clearly feeds into the other. (Global Innovation Outlook – 2004- IBM) **www.ibm.com/gio**

Continuous progresses have allowed the leaving to others (mainly in Asia) of the low-cost mass production, while continuing to fuel a robust economic growth at home. **However, there are indications that the gap in economic growth between Europe and the US may be linked to fewer investments in IT within the EU.**

"Second, ICT are central to boosting productivity and improving competitiveness. 40 per cent of the productivity growth in the EU between 1995 and 2000 was due to ICT1. Economic gains from ICT stem directly from growth and innovation in markets for ICT goods and services and from the use of ICT in raising the performance of businesses. Also, ICT increasingly form an integral part of all industrial and service markets, either through the embedding of ICT components in goods (for example in consumer devices, automobiles, medical devices) or as part of the service offer (tracking of parcel deliveries, e-banking). Empirical evidence suggests Europe's productivity gap with the US is to a large extent explained by its weaker investment in ICT.
Brussels, 19.11.2004 - COM(2004) 757 final" (ICT: Information and Communication Technologies) Sites web

It is then of primary importance to preserve and develop a high level of activity in Information and Communication related technologies in Europe. Nevertheless, this is a real challenge as, if ICTs are widely recognized as major contributors to the economic growth, these are also areas of fierce scientific and technological competition. The long term viability of an ICT industry, and more widely, the proper diffusion of the benefits of the ICT progresses in the society, depend on the existence of an active research environment.

"An indigenous research capacity is essential to be able to master and assimilate technology and to exploit it to economic and societal advantage. This is particularly true for ICT, where innovation moves at an ever faster pace, where the frontiers of research are increasingly broad, and where people and organisations depend more and more on ICT.
Brussels, September 2004 - Strengthening Competitiveness Through Co-operation"

Finally, it is not surprising to see that ICT **technologies account for a growing part of the GDP in the European Union.**

"By enabling access to "knowledge anywhere anytime" ICT fosters new ways of interaction, cooperation, learning and innovation. Technology enhances the capabilities of human beings, individually and collectively, to create and share knowledge. Europe's ICT industry is also a major economic sector in its own right, covering information technology, telecommunications and audio-visual markets. The sector has grown from 4% of EU GDP in the early '90s to 8% today5. While the industry has been unable to compete in all market niches, a strong commitment to innovation has kept European firms among the world leaders in key areas. These include semiconductors, digital media and consumer electronics, wired and wireless communications, and business software."
Brussels, September 2004 Strengthening Competitiveness Through Co-operation"

Also, ICTs are at the core of many of the current dreams for a better life, workplace and economy. In each dream, one easily finds the need for more efficient, smaller and more intelligent memories. Recently, many reports (see the "**Vision 2020, Nanoelectronics at the Centre of Change**" – the report "**Ambient Intelligence : from vision to reality**" from the **IST-Advisory Group**) underlined **the areas where the progresses of ICT (and data storage) will have the deeper and more positive impact**. From the IST-AG report :

- Reinforcing the community and social links through the development of a collective living or community memory
- Civil Security (risk and damage assessment) by intelligent surveillance and new decision support systems processing huge amounts of data
- Home in a networked society, where each individual will have the choice to create a private sanctuary or to connect to the society at a chosen time
- Healthcare (health monitoring, caring for safety of vulnerable peoples such as children…)

When trying to extrapolate the current trends, a key driver for a wider and more profound impact of ICT will be the pervasiveness of Computing and Data Storage in the everyday life.

"This next wave of technologies will make systems "smaller, cheaper, and smarter" and "always best connected", and their applications even more wide ranging. It will open the door to new networked devices and systems that will enable people to interact with their surroundings and with each other in totally new ways."
Brussels, September 2004 Strengthening Competitiveness Through Co-operation

To sum up, ICTs are dealing with

"Life comfort, easiness in life, culture, learning, and preparing/preserving the future"

and **the progress of the ICTs depends on** tremendous and **parallel progress** in the performances, availability and versatility of **mass data storage components**.

3.2 Mass Storage Technologies

3.2.1 Data storage everywhere - A deep impact on citizen life and work - Technologies going to citizen

The need of more and more "memory" is shared by all applications of ICTs such as enhancing life comfort and security, leisure, education, business and improving work productivity. Generally speaking, mass storage technologies and memories must fulfil at least the first of the following requirements, and increasingly all:

- Conveniently store huge quantities of information, often with stringent requirements on data density (memory size) and on security
- Process this information to allow practical and efficient retrieving of the stored data
- Transfer the information at the highest transfer rate

One of the most striking revolutions of the two last decades is the present pervasiveness of mass storage technologies – optical, solid state and magnetic memories are possessed and/or actively used by almost all citizens for leisure, business and work. Furthermore, this information is becoming more and more digital (vs analogic), as this is the most efficient format for recording, storing, and exchange.

"Storage everywhere" Henk van Houten, Wouter Leibbrandt
The new everyday – View of ambient intelligence- (Philips)
"Today, we all make considerable use of digital storage in the home: CDs, DVDs, solid state devices, and computer hard disks and diskettes. As the quantity of "digital contents" available in the home grows- whether coming from the Internet or multi-channel TV-based services- storage will occupy an increasingly central role in the connected home. Our consumer electronics equipment itself is becoming increasingly digitalized, with digital interfaces between consumer systems also starting to emerge. As a result, digital data storage media, such as hard disk drives, and solid- state memories, already familiar from computing, are now being incorporated into home entertainment and other domestic systems. Ultimately, this will lead to a situation in the ambient intelligence home where storage will make stored data of any kind available to users, anywhere and at anytime, in a responsive and transparent way, while the technology remains unobtrusively in the background. But what sort of technology will that be? How will the material be physically stored? More importantly, perhaps, once stored, how will we find it again, and having found it, what will be able to do with it?"

Tomorrow, more and more data will flow from a complex network of sensors and wired or wireless components, for health, culture, agenda, work… Beyond the enhancement of memories capabilities, handling such a flow of information while preserving security (no loss of data), privacy and accessibility is the key challenge. This will require the combination of all available innovations in the memory technologies, and radical evolutions in the treatment of the information (sensor level, processing level, collecting level, back up level…).

"As ICT based applications become more available, there is an increasing need to make them compatible: e.g. the convergence between fixed and wireless networks and between telecommunications and audiovisual provision. Interoperability has many facets: for network operators, it means to be able to interconnect with other networks; for content or service providers, it means being able to run a service over any suitable platform. For consumers, it means the ability to purchase a device and use it to access services and download content from different sources."
Investing in research: an action plan for Europe Brussels, 4.6.2003

This huge flow of data is used to improve work productivity, health monitoring, in new leisure applications (games…), education… Finally, it comes clear that **data storage is associated to all ICT applications – and that, very often, the enhancement of the performances of the memories is the driving force leading to new applications** : CD to DVD (audio to video…) to HD-TV with new DVD generations, new applications for work and leisure on the PC (hard disk capacity)...

The need to increase the capacity of the memories has often been discussed during these last 20 years. However, **the fast progresses of the memory performances have never been able to outreach the needs of the consumers and the industry**. Basically, this is due to the fact that **new applications appeared continuously**. Nowadays, the dreams are so diverse and exciting that it seems this process will never end. Once again, this is allowed by the unique the combination of affordability (for users) and the fulfilment of so many deep expectations and needs (from the consumers and the industry).

3.2.2 The memory… always a strategic part – research on generic technologies

By itself, a memory is always a strategic part within an integrated component. Remarkably, the market supported continuously many kind of memories (optical, solid state and magnetic). For each one, the capacities increased exponentially (Moore's Law) over 20 years, either continuously or by large discrete steps (optical memories) (Figure). Perhaps surprisingly, each technology demonstrated unique performances, such as the highest data density and capacity (Hard Disk), media removability and low cost (CD, DVD), high speed (solid state memories)… and thereby secured its own market. The dream of the unified memory proved inaccessible, even to the present day.. As a result, a creative and active research has been performed in diverse areas of the modern technologies, with a wide and large impact. Indeed, beyond their own areas of applications, the technologies developed for "Mass Storage Memories" played a key role in the evolution of the new technologies from the beginning of the 20th. This race towards increased performances implied the use and improvement of diverse and wide areas of the available technological know-how, to the point that **many modern technologies in mechanics, semiconductors, magnetism, and optics**

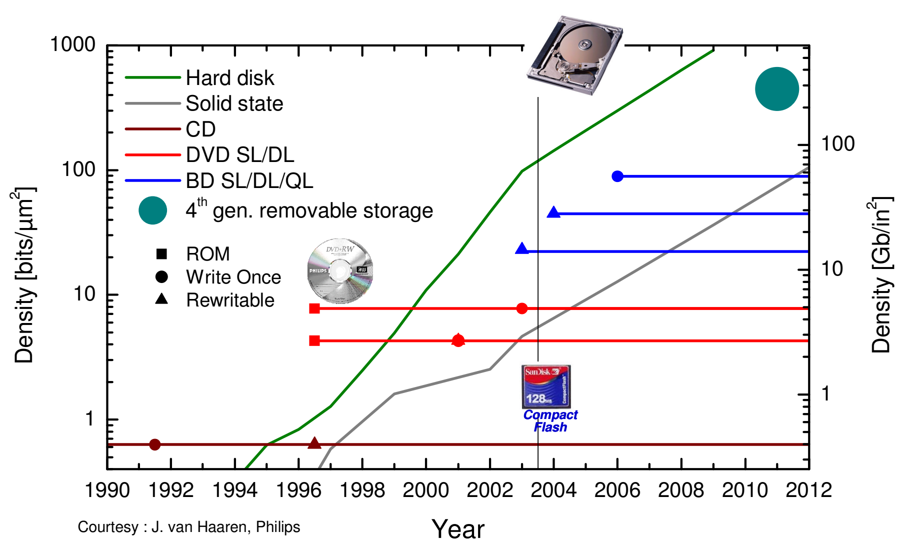


FIGURE 3.1 :

Evolution of the data densities for the main technologies for mass data storage

(Note that the optical technologies progress by wide step at each generations (CD, DVD…) while magnetic media (Hard Disk) and solid state memories (Flash) experience a continuous evolutions.

have been applied and very often developed or pushed to new performances to produce new, high density, and fast, memories. For instance, the progresses obtained in these generic technologies led to breakthroughs used in miniaturized actuators (drives), computers, telecommunications…

3.2.3 Dreaming of the future: new applications

As already pointed out, it has been consistently impossible to imagine the realms of applications opened by the increasing capabilities of the Mass Data Storage devices. Bill Gates (Microsoft founder) is famously said to have declared that computers would never need more than 640KB of RAM! True revolutions such as home video, video games, the widespread use of USB keys to exchange information, PDA's, digital monitoring and recording on the workplace… were unthinkable in the Eighties.

Now, as seen on Figure 1, people are looking with more confidence towards the future of Mass Data Storage, forecasting a continuous surge of the capacities (and densities, thereby implying that smaller and nomade devices will be more and more available) – and the paradigm has reversed**: let us dream of what could be done with the memories that will be available!**

Recently, it has been underlined that the old Memex dream, first proposed by Vannevar Bush [As We May Think, The Atlantic Monthly, 176(1), July 1945, 101-108] could soon be feasible: "a device in which an individual stores all his books, records, and communications, and which is mechanized so that it may be consulted with exceeding speed and flexibility". As the needed technology may soon be available if Mass Data Storage progresses continue, Microsoft took over this challenge under the project MyLifeBits (http://research.microsoft.com/barc/MediaPresence/MyLifeBits.aspx). Similar goals are shared by other groups, such as the CONFIDENT project (http://www.clve.fr/confident.htm, that is a French think tank). The underlying idea is to be able to propose a new device, able to store all the information encountered by someone during his whole life (video, photographies, books, documents…) and to efficiently retrieve the needed one upon request.

Such devices would efficiently answer to the need of most people to save (to see later) old photographies, letters… that have such a strong emotional values – they may also find more targeted applications such as health monitoring, with the continuous recording of body parameters, that would allow the physician to trace back to its origin any medical problem . Basically, huge amounts of information should be stored, most of it being accessed only from time to time. The size of the requested memory would be in the TBits range, and **new ways to handle the complexity of the stored information have to be designed, from innovation in software and hardware (new components associating many kind of memories…).**

Realising such a dream and similar ones hence requires huge progress in the performance and the architecture of memories. However, a reasonable analysis of the current trends supports the idea that the needed technology may be available within 10 years if the innovation rate is maintained.

Beyond the specific and emblematic Memex dream, it is worth reminding that all the diverse and exciting visions of progresses building upon progresses in ICTs will require progress in mass data storage technologies as a required foundation.

What has already changed:

In 1990, a EU citizen (quite an IT active one as already having a PC) could rely on:

a few tens of **CD audio** (20 GB) – he has to buy these and can't record himself the data

a **PC** with an hard disk around 40 MB

only a few of the other devices he is using (such as his car) may have digital memories

In 2005, the same citizen is far more likely to have a PC, and certainly possess extensive audio and video data – furthermore, most of the data are now personally created

a few hundred **CDs** (audio, data) and a few tens of **DVD** (video) : 200 GB (optical memory)

a **PC** with an HDD capacity around to 300 GB (magnetic memory)

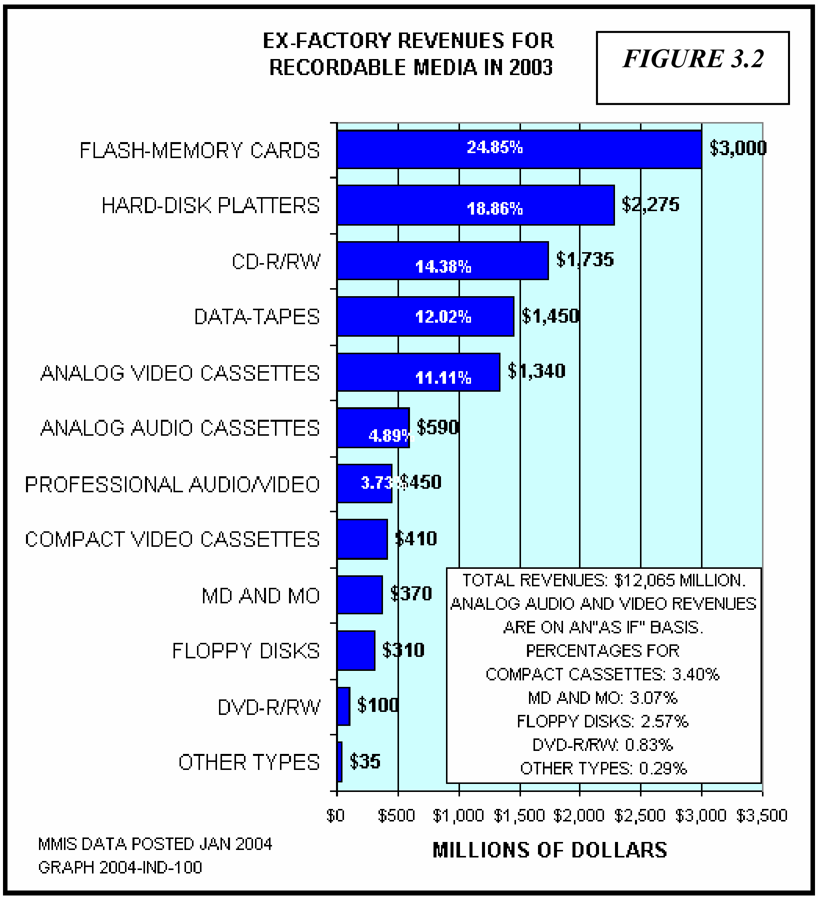
a **PDA** with a memory in the MB range, the same for his **mobile phone**, plus may be a **USB key** (256 MB range) – (all with solid state memories)

he is recording and storing digital photographes and personal videos (**digital camcorder**) – here, he is using solid state, magnetic and / or optical memories and can transfer the data on DVD or HDD

in addition, he is conveniently using a large amount of memories almost without taking care (in his car, in banking activities…)

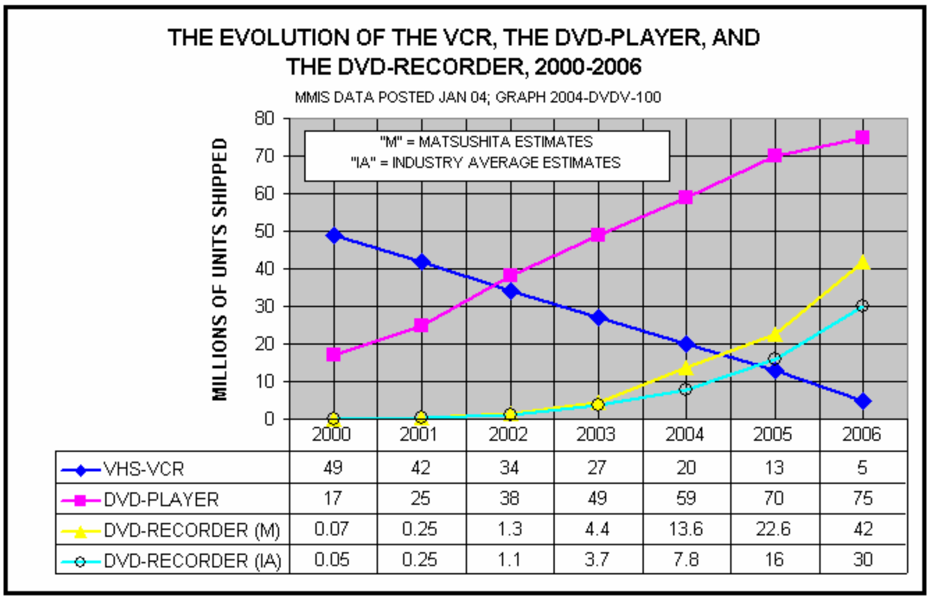
3.2.4 The markets - the European position and industry

The economic activity associated with mass data storage has increased continuously during the past decades. Due to the fact that the memories are, in most cases, a part of the final product sold to the consumer (exceptions are optical media and USB keys), precise data on the revenues for the industry are quite difficult to assemble. In any case, mass data storage generates a large economical activity, as shown in Figure 2.



When examining closely the shares of HDD, tapes, optical and flash memories, one may be surprised to see that the global revenue is quite equally shared – in spite of the fact that we compare established and more recent technologies, wider and more emerging markets. **This is understandable as, on many markets, the most recent products, with the highest performances, generate the highest revenues**. This is true for the Flash currently, and underlines **the critical role of innovation in this competitive area**.

To understand the importance of the revenues associated with the data storage activities, one should also keep in mind the fast penetration of the successful technologies on the market, once adopted by the consumers. Here below, we provide the striking instance of the video players and recorders.



	2000	2001	2002	2003	2004	2005	2006
VHS-VCR	49	42	34	27	20	13	5
DVD-PLAYER	17	25	38	49	59	70	75
DVD-RECORDER (M)	0.07	0.25	1.3	4.4	13.6	22.6	42
DVD-RECORDER (IA)	0.05	0.25	1.1	3.7	7.8	16	30

Figure 3.3 : DVD and DVD recorders, number of shipped units

The DVD market exploded in 4 years only, and brings the old VHS on the edge of disappearance. Now the newest product (DVD writer) knows an exponential progression. Other mass data storage technologies enjoy a similar and healthy growth. For instance, the **Hard Disk is now coming out of the PC world and invading a wide range of new applications**, as drives are provided with new performances and form factors (small ones, nomadic, with reduced energy consumption…). As a result, both the number of shipped units and of the storage capacities are rapidly increasing. For this reason, the Hard Disk currently supports more than 90 % of the newly stored information each year (www.sims.berkley.edu/research/projects/how-much-info-2003). For solid state memories, the leading product on the consumer market is now the Flash Memory, as the ongoing race towards higher capacities meets a strong consumer demand. On the industry side, it is expected that the available capacity will double each year at least until 2008. Companies' positions are rapidly evolving as a result of industrial policies and of the evolution of the production facilities.

Main players in Flash memory field are reported in the table here below, which shows also the strong vitality of the market. Intel, which had been holding a leading position since the beginning, has dropped to the 4^{th} place, overtaken by Far-East producers of NAND Flash memories, like Samsung and Toshiba.

2003 Rank	2002 Rank	Company	2003	2002	Pct Change	2003 Marketshare
1	2	Samsung	2952	1062	178%	23.8%
2	5	Toshiba	1912	703	172%	15.4%
3	3	AMD (Spansion)	1740	735	20%	14%
	4	Fujitsu (Spansion)	-	717	-	-
4	1	Intel	1674	2049	-18%	13.5%
5	8	Mitsubishi (Renesas)	1040	374	105%	8.4%
6	6	Sharp	819	671	22%	6.6%
7	7	STMicroelectronics	783	698	29%	6.3%

Table 3.1: ranking of top 7 Flash memory manufacturers (source: Web-feet research)

The European position is quite good in Mass Storage Technologies, with a lot of large and small companies, with an active research and a number EU based production facilities.

- **On the market of solid state memories, STMicroelectronic***s* has been active since the beginning, starting from EPROM, and including EEPROM, Smart Cards and micro-processors with embedded Non Volatile Memories. **Philips Semiconductors** has a tradition in the development of embedded EEPROM for Smart Card applications. The company has recently extended its interest to embedded Flash for micro-processors and ASIC (140 nm and 180 nm technologies), and has demonstrated products with up to 7Mbit embedded Flash. Philipsn Freescale and STMicroelectronics collaborate in the area of MRAM. Philips Consumer Electronics is also a large user of Non Volatile Memories (NVM) for consumer products. **Infineon**, which was ranked world-wide n°6 semiconductor manufacturer in 2002, has also an important tradition in the development of embedded NVM for Smart Cards, and is currently the market leader in the field. It is also actively pursuing the development of embedded Flash for microprocessors, and is prototyping the 130nm generation. Infineon is working on several emerging NVM technologies; these include MRAM, FeRAM and polymer memories.

European Research Institutes and Universities have reached a position of excellence on the subject. Among the most important ones, one may cite the IMEC and the LETI

- **On the market of optical data storage,** the EU position is strong. **Philips** develops optical drives, key components and new optical discs in Eindhoven and Wetzlar, and driver ICs in Eindhoven, Leuven and Southampton. There are various industrial activities in the Eindhoven area, like **Anteryon** for optical components and Singulus for mastering equipment. **Thomson** has optical storage research activities in their laboratory in Villingen (Germany), and the Thomson subsidiary Technicolor has several replication production sites for DVD and CD in Europe. **Unaxis Data Storage Ltd** (Liechtenstein, UK) and **Arburg** and **Singulus** (Germany) are major manufacturer of optical disc production lines. **Plasmon Data Systems** (UK) makes professional optical disc archiving systems for enterprises. Smaller actors such as **Infinite Data Storage Ltd** (UK), **Lasertrack Ltd** (UK)… demonstrate the vitality of the field. Europe has a number of replicator companies like **MPO** (France), **Sonopres**s (Germany), **Sentine**l (Belgium) and others. **Bayer, Ciba Geigy** and **Clariant** produce polymers and dyes for the optical storage industry. **Toptica** (Germany), **Dr. Schenk** (Germany), **Datariu**s and **AudioDev** (both Austria) make professional testers for optical discs.

A **number of European universities and research institutes** have had significant contributions to the optical storage field. The LETI (Grenoble), Universities like Exeter, Hanover, Plymouth, Aachen, Delft, Dublin, Nijmegen, Cambridge, Imperial College London, Lancaster, Limerick, Brussels, Amsterdam, Ghent, Eindhoven, Manchester and others are active in research in this field, including through past EU funded projects. In this dynamic environment, start ups like **P3 Holographics Ltd** (UK) are actively pursuing breakthrough such as holographic storage.

- **On the market of magnetic data storage,** the EU position is weaker. For Hard Disk Drives, **Seagate Technologies** (Ireland) remains the only real European player (locally producing heads and substrates) after IBM sold its hard disk division to Hitachi and closed its Germany and Hungary plants. However, other companies such as **STMicroelectronics** directly benefit from the progresses of the HDD by providing key electronic components to be integrated in the final device. Smaller companies are active on the exploration of new media technologies, such as **Nimbus** (UK) or **Obducat (**Sweden), that could take an important part in patterned media development, or **Nanomagnetics** (UK) that is working on self organized magnetic media. In addition, **Naomi technologies** (D), a spin off of former IBM Mainz, proposes electronics and magnetic technology developments for recording, sensors, MEMS, etc… On the market of magnetic tapes, the situation is rapidly evolving, European major Tandberg transformed into **Tandberg Data** (integrated solution company), **Tandberg Storage** (hardware) and **O-Mass,** subsidiary of Tanberg Storage and Imation (30% share), a US company. O-Mass develops innovative solutions such as 64 channels recording with magnetooptical readout. **Naomi technologies** (D), a spin off of former IBM Mainz, can also play a role in electronics, signal processing and heads development. Many companies such as **Storagetek** France (F), **Imation** Germany (D), **Hi-Stor** (F)… propose integrated backup technologies and are strongly interested in what technological breakthroughs could bring to tape storage. Other actors, such as **Hewlett Packard** (UK), and many small companies (such as **Data Recording Heads Ltd**, (UK), **eMag Solutions** (UK)) have a significant activity on the market of tape heads or drives. The **Xyratex** company in Havant (UK) is also a significant player - over half of the world's disk drives produced today are tested on Xyratex equipment. Xyratex are also a world-player in the development of storage arrays and networked storage based on hard disk solutions.

In spite of the relative weakness of the EU industry in Magnetism, especially for HDD, the quality of the research institutions is undoubtedly at the top international level, mainly in France (Orsay, Grenoble), England (Manchester, Belfast), Germany, Belgium and Holland. For this reason, on emerging technologies such as the MRAM (Magnetic Random Access Memories), a favourable starting point has been reached, as the most important discoveries that led to MRAM came from European research. Now, the MRAM technology optimised by the IBM-Infineon research team is being developed in France by **Altis Semiconductor**, a jointly owned subsidiary, where a MRAM R&D Center is being set up at the 130nm/200mm Altis production plant. In addition, the Motorola MRAM technology is now also developed in France by the **Crolles II Alliance** (ST Microelectronics, Motorola, Philips), for production in the new 90nm/300mm Crolles plant near Grenoble – and several start-ups are created throughout Europe, to provide innovative developments in parallel with the R&D efforts in major companies.

Finally, it is worth underlying that **the mass data storage field is highly interdisciplinary, and provides in excellent training opportunities for young scientists**.

3.2.5 The IMST conferences – The White Book

As can be deduced from the previous pages, mass data storage technologies are a highly competitive, creative and active field for the modern research in industry. Traditionally, it has been divided in between optical and magnetic data storage, plus next solid state memories. However, more and more technologies, such as the MRAM memories are now developed at the crossroads of the pre-existing research areas. In addition, the diversification of the applications and of the products (smaller hard disks or optical memories, higher capacities for solid state devices…) create wide range of applications where all these technologies are competing on the same markets. However, historicallythere has been no real European "mass storage community". Indeed, the three most widespread mass storage technologies (optical memories, solid state memories, magnetic memories) belong to different academic communities, and are often developed by different companies.

The creation of the Innovative Mass Storage Technology workshop built up on these considerations : competing on the same markets, sharing some of the new technologies, the research and industrial communities of mass data storage need a common forum. Indeed, the industry can no longer develop its activity at the moving frontier of knowledge in any of the fields of the mass data storage without having a close look to competing technologies. In addition, magnetic and optical memories have now such high density performances that they are going closer to fundamental limits (diffraction limit, super-paramagnetic limit) that will require technological ruptures to allow for further progress in data density. As this has been recognized about 10 years ago, research labs are now actively pursuing the development of radically new paths to support future developments, such as probe recording.

The IMST conference has been designed as the perfect forum to provide a wide overview of the state of the art in all these areas of mass storage: optical, solid state, magnetic… and emerging technologies. A key for the success has been the incentive put by the first scientific committee on the mixing of both academic and industrial communities. After a quick maturation through the two first events (Grenoble 2001, Exeter 2002), the IMST workshop reached a full success in Grenoble in 2003: about 150 participants came from eleven different European countries, plus invited and contributed speakers from Japan and USA, and a large number of major companies and start ups were represented (Philips, ST Microelectronics, Thomson, Thalès, MPO, IBM, Seagate, Sony, Grandis…)… For all the participants of IMST 2003, this was a unique opportunity to compare and evaluate the progress made and the opportunities opened by the most advanced teams in the competing technologies that are otherwise presented in very distinct forum. IMST 2004 was organized in Aachen (Sept. 28,29) and capitalized on this success and on the new appetite from the community for this specific event. The number of participants reached 150 persons with the participation of leading industrial international companies (Samsung, Panasonic, Philips, Thomson, ST, IBM, etc..).

For the future, an agreement has been reached between the organizers of IMST and of E-PCOS to join these 2 conferences in 2006 during the MINATEC week at Grenoble. This event will be largely open to the world scientists and industries. The number of participants is foreseen to reach more than 200 attendees.

The elaboration of a "White book" for mass storage technologies road map is the continuation of this work. It is targeted towards the European scientific and industrial community, and to the European Commission, and proposes a vision of the strategic areas that are worth of funding to maintain or develop a strong European scientific and technological research in key mass storage technologies.

This work has been done with European academic, public research and industrial experts in:

- Solid state technologies
- Optical technologies
- Magnetic technologies
- Emerging technologies

The background of each expert has been reinforced by a call to the IMST participants to contribute with ideas and suggestions that led scientists from a number of labs and companies to contribute to the report. This has been a collaborative work. The content of the report results from the aggregation of the individual knowledge of the involved experts and of these contributions from the community.

This report results from the common work of the listed individuals (see page 2), with the additional support of the EU Mass Data Storage community.

4 Overview of the main technologies for mass data storage: technical challenges, market trends, European position

4.1 Solid state memories

4.1.1 Needs and relevance

Our world at the beginning of the 21st century is fundamentally and irreversibly changing. We are just entering the IST age characterized by a third industrial revolution after those brought by steam and electricity. ***The engine that drives this revolution is Microelectronics and more particularly the CMOS devices based integrated circuits that constitute over 75% of the world's semiconductor consumption. Through its dramatic increase in performance CMOS Microelectronics is the enabling technology at the heart of major progress of all the IST applications.***

Electronic systems include two main functions: data processing and memory, and together they make up for more than 65% of overall semiconductors' market. The growth of memory usage has been explosive, and the famous sentence by Bill Gates 'I do not see why somebody should need more than 64K of memory" has been often quoted as an example of the incapacity to understand the future, even for those who were creating it.

At the moment there seems to be no sign for a slowing down of memory requirements: on the contrary the diffusion of broadband communication and digital appliances, the transmission of images, and the constant demand for better quality of images and sound, is creating an ever increasing need for large memories in a variety of new media: cellular phones, PDA's, cameras, set-top boxes and so on.

4.1.2 Memory Technology

Memory Cell

Solid-state mass-storage memories are based on Non Volatile Memories (NVM), almost exclusively using floating gate technology. The main advantages of these memories are the use of consolidated technology, the lack of any mechanical parts, which results in stronger ruggedness, lighter weight, smaller form-factor, better reliability and lower power dissipation. Comparing the NVM with other types of mass storage memories , today they still present a lower density, in terms of Megabytes/square centimeter, and an higher cost, in terms of pure cost/bit. Nevertheless they have a well established market in the medium/low density (at the moment in the range of 128Mbytes-4Gbytes), thanks to the better granularity and the programming throughput at an acceptable cost. Moreover the Moore's law will insure a constant doubling of memory capacity every year, at least for the next 10 years, giving a constant memory density increase.

At the moment the main reprogrammable Non Volatile Memories are based on the stacked floating-gate cell structure, and the industry standards make use of two architectures (fig.1):

- **NOR** Flash memories, characterized by faster access, but larger cell size, which are used mainly for code storage;
- **NAND** Flash memories, characterized by longer access times, and higher programming voltages, but with a smaller cell size, used mainly for data storage.

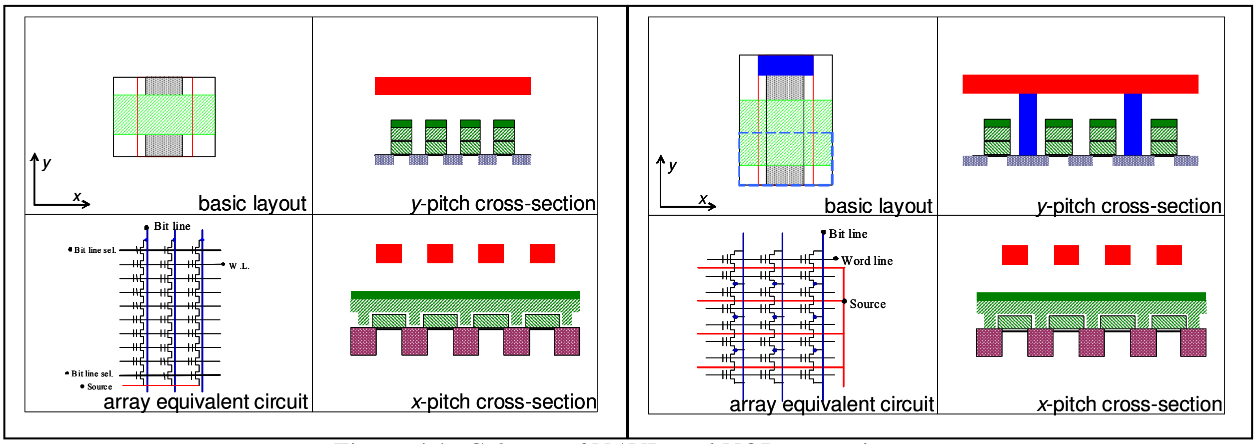


Figure 4.1: Scheme of NAND and NOR memories

Evolution of Flash memories is following the Moore's law, and closely tracks the one of DRAM. The evolution of cell size is reported in Fig.2, and has achieved a reduction of a factor of 30 in 10 years.

The most recent announcements give a cell size of around 0.08µm^2 for NOR memories at 90nm technology node (Intel, STMicroelectronics, Samsung), and around 0.025 µm^2 for NAND at 70nm technology node (Samsung, IEDM 03).

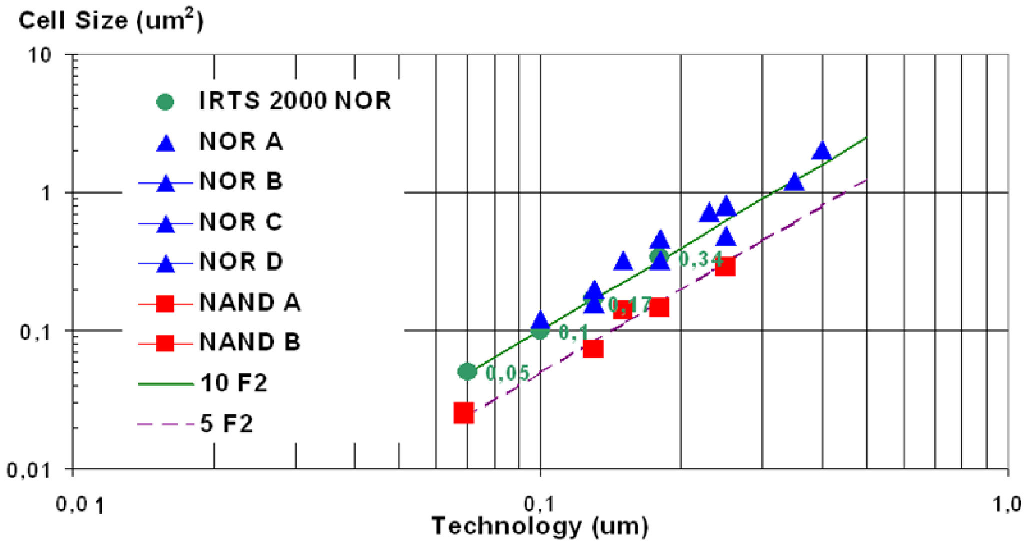


Figure 4.2: evolution of Flash memory cell size

Mass storage solid state memories are realized exclusively with NAND memories, due to the lower cost by bit and higher programming throughput. This last, together with the cost, is the actual limiting factor for NOR memories in the mass-storage application. The Multi-Level Concept, i.e. the possibility to store two bits in one cell, has been proposed by Intel in the NOR technology to reduce the cost differential, but it is not competitive enough with the faster programming throughput of NAND. Moreover, NAND technology already started offering devices with 2bit/cell. The use of Multi-Level storage has its main drawbacks in reduced speed and reduced signal-to-noise ratio and error immunity. The latter can be solved by design, with Error Correction Algorithms, but introducing further delays in the access time. The main drawback of NAND memories is the relative slow access speed. The problem can be partially solved by adding a buffer memory to improve throughput, therefore it is gaining increase acceptance the use of multi-chip memory modules, including in the same package a NAND Flash and a DRAM or SRAM.

With the above listed limitations it now generally accepted that NAND technology will dominate mass-storage, while NOR technology will still be preferred for direct code execution.

The ITRS roadmap foresees a continuous reduction of the cell size (Tab.1), even if the relative cell size (expressed in terms of minimum feature size) is assumed to increase.

		Year	2004	2007	2010	2013	2016
		Technology node (nm)	90	65	45	35	22
Flash	NOR	Cell Size (λ^2)	10	11-14	12-15	13-16	14-17
		Cell Size (μm^2)	0.101	0.053	~0.034	~0.018	~0.010
Flash	NAND	Cell Size (λ^2)	5.5	4.5	4.5	4.5	4.5
		Cell Size (μm^2)	0.045	0.019	0.011	0.006	0.003

Table 4.1: 2003 ITRS roadmap for NOR and NAND memories

However physical limitations exist that could further reduce the margins for cell size reduction, unless substantial progress is made in critical areas, even if recently Intel expressed its confidence in the possibility to extend floating gate technology to the 45 and possibly 32nm nodes[1]. These limits are essentially related to the difficulty in reducing tunnel and interpoly dielectric thickness, due to trap-assisted leakage currents.

Innovative solutions are requested to follow the ITRS roadmap beyond the 45nm node. They can be roughly divided into two categories:

- *Evolutionary* technologies, still based on variations of the well-proven floating gate architecture, making use either of new materials (nanocrystal or nitride traps for the storage node, high-k interpoly dielectric, multilayer "crested" barrier for tunnel dielectric) and of multibit/cell storage. An ever increasing importance must be given to signal processing techniques, like advanced coding and ECC, both to compensate for the reduced signal-to-noise ratio, and to take care of the statistical dispersion related to very large memories. These approaches present the advantage of re-utilizing large part of existing know-how on device physics and reliability.
- *Disruptive* technologies, based on the introduction of new storage mechanisms, like magnetic storage (MRAM), Ferroelectric Storage (FeRAM), Phase Change Materials (PCM memories), or, more recently, a variety of polymers and organic or inorganic materials that hold the promise for permanent storage. The main differentiation with mainstream technology is in the storage mechanism, that is not based on charge storage but on:
    - Charge displacement, like in crystalline ferro-electric and polymer ferro-electric

[1] S.Lai, "Recent Trend of NVM Technologies, in " Nikkei Microdevices Memory Symposium, Tokyo, Dec. 18, 2003

- Resistance change, related to magnetization changes, phase changes, charge transfer in polymers, Schottky effects in complex metal oxides, conductive filament formation.

A further distinction is among memories that are realized with cross-point cells, either with a continuous storage layer, or with "islands" of storage medium, localized in vias, and active matrix memories, with an active device (MOS or bipolar transistor), in series to each memory element. The first approach is of course the most attractive, opening the way to the stacking of multiple memory layers, but the reading of the cell is quite complex, and even programming requires the use of intermediate voltages, to reduce parasitic programming effects.
The second offers better safety and signal-to-noise ratio, and it is more easily integrated in current memory architectures, but does not offer any chance of reducing cell size below 6-8λ^2.

Most of the disruptive memory effects present also advantages in terms of programming speed and power, which could make them suitable to replace also DRAM's, thus realizing the designer's dream of a single "Unified Memory".
Ideally, the ultimate „unified memory" aims at replacing conventional embedded and stand-alone memories, i.e. native SRAM and DRAM, as well as the embedded DRAM, Flash and EEPROM memories in a CMOS process. However, even if all memories cannot be united into a single type of memory, the target should be to at least unify the technologies to produce the fundamental memory cell. This unified technology platform offers the possibility to provide different versions with various balances of speed, density, endurance, etc… depending on the application at minimal costs and efforts.
Even if this new memory platform is targeted to solve issues with conventional memories expected at feature sizes below 50 nm, the technology base may be also used at larger dimensions due to additional features compared to today's standard memories, e.g. non-volatility, low voltage, small cell size, and reduced cost.

The basic properties of the mainstream technology, and of the alternative solutions that have reached a reasonable maturity stage, are reported in Table 2.

	Flash	NROM (nitride traps)	FRAM (ferro-electric)	MRAM (magnetic)	PCM (phase change)
Relative bit size	0.25 - 1	0.5 - 1	3 - 10	1 - 3	0.5 – 2
Relative mask count	1.1	0.9	1	1	1
Scalability	Fair	Fair	Poor	Poor	Good
Multilevel Capability	Yes	Yes	No	No	Yes
Endurance	10^6	10^5	10^{10} (destructive read)	$>10^{14}$	10^{12}
Data alterability	Pgm: bit Erase: sector	Pgm: bit Erase: sector	Pgm: bit Erase: bit	Pgm: bit Erase: bit	Pgm: bit Erase: bit
Data retention	>10 yrs	>10 yrs	>10 yrs	>10 yrs	>10 yrs
Write time	µs/ms	µs/ms	<100ns	<100ns	<100ns
Write power/B (VxI)	5V x 1mA	5V x 1mA	3V X 100µA	1.8V X 10mA	3V X 1mA
Maturity	Volume prod.	Production	Limited production	Test device	Test device

Table 4.2: Comparison of basic characteristics of the main current NVM technologies

The main problems of the alternative technologies, which have been investigated till now, are the lack of know-how on material properties and reliability mechanisms, the scaling potential, which does not seem to be much better than for floating gate Flash, and the need to mobilize a large development effort also in the field of basic material studies and equipment development. Only trap-based memories, which are the closest to conventional Flash, seem to be able to compete for mass-storage.

The combination of relative bit size and cell scalability limits the use of current FRAM and MRAM approaches to special performances and embedded applications, even if the same storage mechanism could be used in new memories with more advanced materials (e.g. ferro-electric polymers) or new approaches (e.g. thermally assisted switching (TAS) and current-induced switching (CIS) for magnetic storage). At the moment, only Phase Change Memories show some potential for NOR Flash replacement, but in the current architectures, their scalability is limited by the presence of one transistor in each cell.

4.1.3 Status of the Market

At the moment (2004) the market of Non Volatile Memories is still dominated by NOR memories, also because of the lower unit price of NAND memories, but the balance will shift, as shown in Fig. 3, with the increasing diffusion of consumer applications, which require more and more easily portable storage media. The use of NAND memories is being considered also for mobile phones, because of the increased memory demand, related with the transmission of images. As discussed before, multi-chip devices, combining NAND Flash and SRAM or DRAM are also likely to form a considerable part of the market.

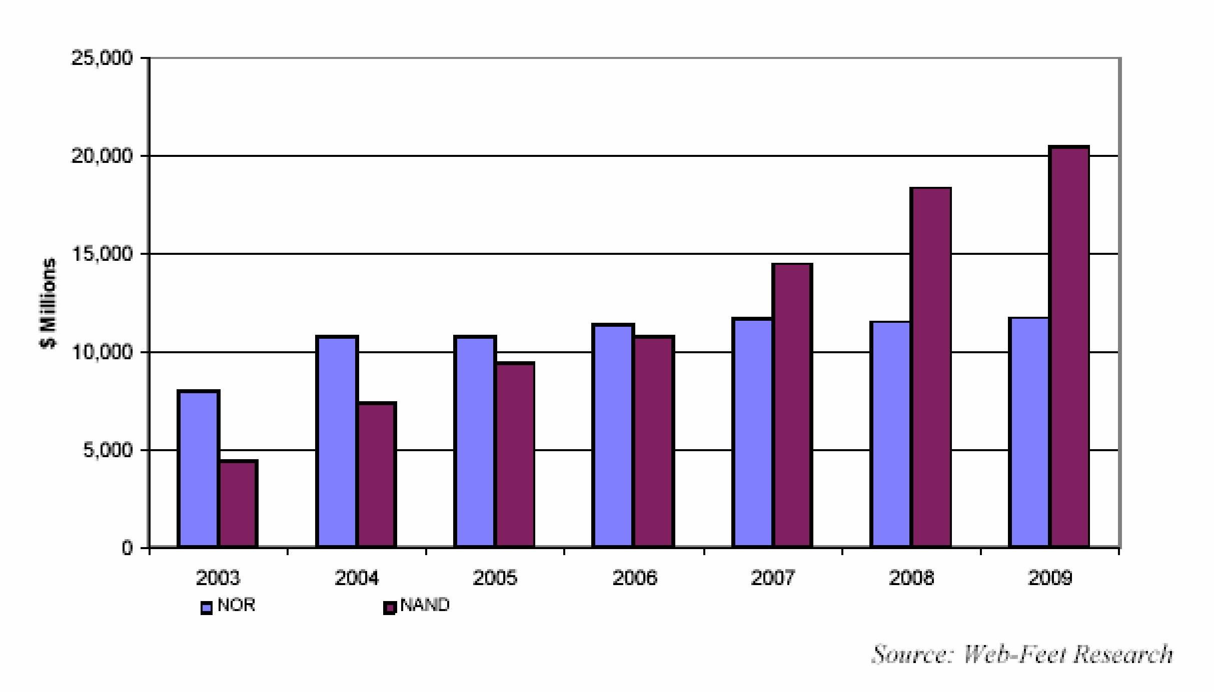


Figure 4.3: NOR and NAND market trend.

At present, the market of solid-state mass storage is dominated by NAND and NOR Flash memories. The main applications are cellular phones, PC drives, in particular USB keys, and portable consumer, like Digital Still Camera, Video Camcorder, MP3 Player, PDA/ GPS/ Ebook, Video Games. This market segments will represent in two-three years more than the 70% of the overall NVM market.

Among the driver application, the Flash cards and USB keys will play the main role. Flash cards have to be considered as a dedicated system for mass storage in which the NVM technology will merge with the logic technology – the system needs a microcontroller in order to manage the huge amount of memory – and the package technology – the microcontroller and the memory chip must be embedded and packaged together.

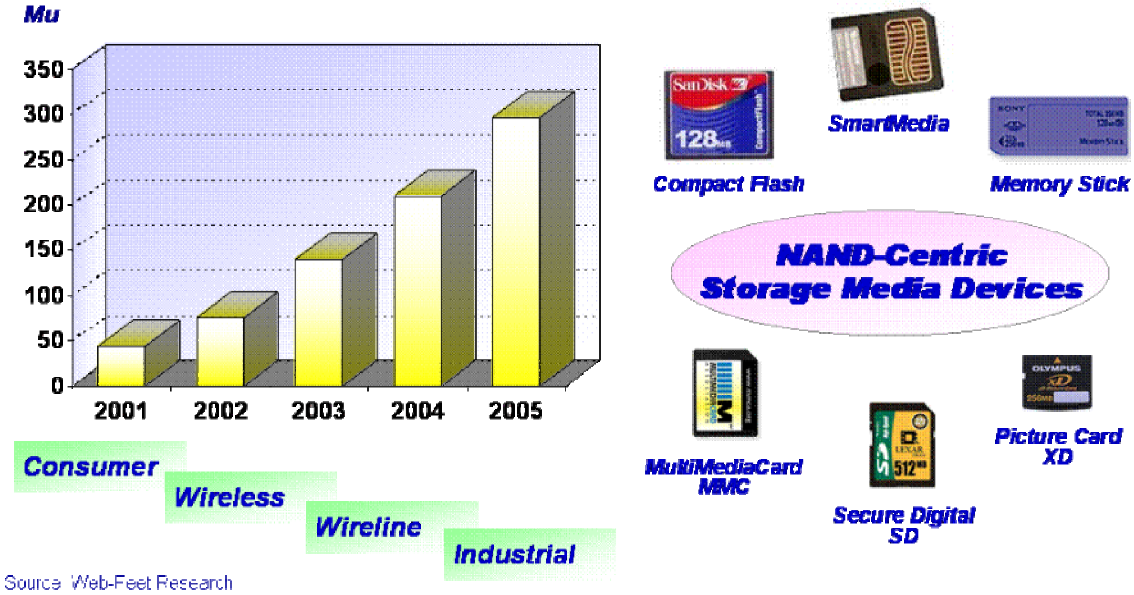
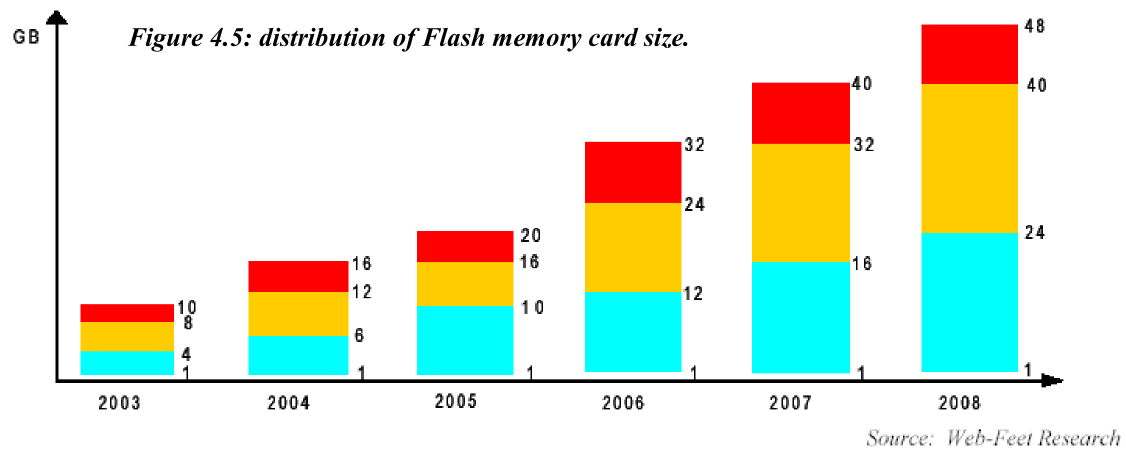


Figure 4.4: Flash cards formats

Today different types of Flash cards are present in the market: Compact Flash, SmartMedia, Memory Stick, MultiMedia Card, Secure Digital, Picture Card (see figure 4). They differ mainly for the form factor and for other minor specification. A standardization of the card format and data transfer protocols does not exist yet. But all of them consist of the same NVM technology, NAND memory, with a microcontroller on board. The microcontroller, besides acting as interface between the different memory chips and the external world, is actively managing the Error Correction Code that can guarantee a better reliability and a longer life of the Flash card system.

Figure 4.5: distribution of Flash memory card size.



The present market for the Flash card is in the range of 150million unit per year. It is expected to double in two years, reaching the 300million units. Obviously the portable consumer, like the digital still camera and the MP3 player, are the main driver for this mass-storage system. The general forecast is for a strong increase in average size of Flash card, as shown in Fig.5. Since the card format is fixed, the increase can take place only by increasing the chip memory content.

The introduction of disruptive technologies, which could offer NVM storage with higher density (and lower cost) than Flash, and with at least comparable programming and reading speed, could further accelerate the evolution of the overall NVM market, replacing multi-chip memories, and probably a good part of DRAM's and enlarging the Flash cards application. An advantage of this kind of applications for Non Volatile Memories is given by the relatively relaxed performance requirements (latency is not a major problem for mass-storage, and temperature range is the consumer one), related to the application environment, and to the possibility to introduce error correction algorithms.

In addition to pure memory technology, the realization of Flash cards is requiring a strong research push in two related areas:

- Algorithms for data storage, including compression error compensation
- Packaging technology, in order to stack more memory chips together, to increase storage efficiency.

4.1.4 The role of Europe

Europe has a long-standing tradition in the development of Non Volatile Memories, and even now European companies are very active in the field. The most important European players are:

- *STMicroelectronics*, has been active since the beginning in the development of Non Volatile Memories, starting from EPROM, and including EEPROM, Smart Cards and micro-processors with embedded NVM. It is now number 6 in the ranking of Flash producers, and has recently started, in cooperation with Hynix, the development of NAND Flash for mass storage. A 512Mbit memory has been announced recently. The Company has also, together with Intel, licensed the Phase Change Technology from Ovonyx. A 8Mbit Phase Change Memory demonstrator was presented at VLSI Symposium 2004.
- *Philips Semiconductors* has a tradition in the development of embedded EEPROM for Smart Card applications. The company has recently extended its interest to embedded Flash for micro-processors and ASIC (140 nm and 180 nm technologies), and has demonstrated products with up to 7Mbit embedded Flash. Freescale, Philipes and STMicroelectronics

collaborate in the area of MRAM. Philips Consumer Electronics is also a large user of NVM for consumer products

- *Infineon,* which was ranked world-wide #6 semiconductor manufacturer in 2002, has also an important tradition in the development of embedded NVM for Smart Cards, and is currently the market leader in the field. It is also actively pursuing the development of embedded Flash for microprocessors, and is prototyping the 130nm generation. In the field of stand-alone memories it has established links with Saifun for a proprietary two-bit/cell technology (a 512Mbit NAND memory, based on this concept, has been recently announced). Infineon is working on several emerging NVM technologies; these include MRAM, FeRAM and polymer memories.
- Also European Research Institutes and Universities have reached a position of excellence on the subject. Among the most important ones:
  - IMEC has been developing innovative cell architectures from the early 90's, participating to several research projects with leading industry partners. It has explored several NVM technologies, including FeRAM, MRAM and SONOS. It is currently offering an affiliation program on 45nm Flash technology, to which both Intel and Infineon have decided to associate.
  - LETI has a long tradition in the development of materials and concepts for Non Volatile Memory technology, mostly in cooperation with STMicroelectronics. At the moment it is active in the research on MRAM, PCM materials, and nanocrystal Flash memories.

In the field of more advanced, disruptive technologies, research activities are taking place in all major European companies and research centers, also under the umbrella of funded research projects (e.g. Framework 6 "NOSCE MEMORIAS"). Also a few start-up are present, in general offering advanced solutions in cooperation with major players (e.g. Thin Film Electronics ASA).

4.1.5 Opportunities for Research

Solid-state memories for mass-storage are a quite recent development, and there have been only relatively few research projects on the subject, financed by the European Community. Most of related projects concern either Non Volatile Memories in general, with a special attention to embedded applications, or basic storage mechanisms that could be used for memories. The situation is similar for national-funded projects inside the Eureka Program, the main difference being the lack of small speculative projects, and the focus on embedded applications. A list of the main projects in the field is given in part 7.

To support European industry through the foreseen explosive growth of mass-storage applications, extensive research activities are required that could focus the know-how, which already now exists in different European Universities, Research Centers and Industries. Integration of different disciplines is important.

Considering the timeframe of the planned evolution of solid-state mass storage, there is place for research activities at various levels:

Along the evolutionary path: for the next ten years solid-state mass storage will be based on the evolution of the floating-gate architecture. However, to meet the requirements of the multi-gigabit era, new materials and concepts are needed:

- Integration of new materials inside the floating gate cell, as interpoly material (high-k dielectric multilayers), for the tunnel dielectric (oxide-high-k multi-layers for barrier engineering) and for the storage node (conductive materials with different work function, nano-crystals, trapping layers).
- Process integration for Non Volatile memories, including the manufacturing of different gate oxides (to handle the very different programming and reading voltages), problems of stress in the substrate, the possible inclusion of vertical structures (fin-FET memories, elevated source/drain, etc.).
- Defects and parasitic conduction mechanisms need to be characterized, their physics understood, proper modelling tools developed, and reliability screening procedures established. This activity will require an improvement of order of magnitudes in the more sophisticated analytical methodologies, and development of new ones.
- New design approaches must be developed to efficiently mask single-bit failures, like the ECC in the Flash memory cards, and define proper storage algorithms and architectures.
- Research along the evolutionary path is a pre-requisite for any further research, since it will establish a benchmark, and probably, without it, there would be no European industry left to exploit more advanced approaches.

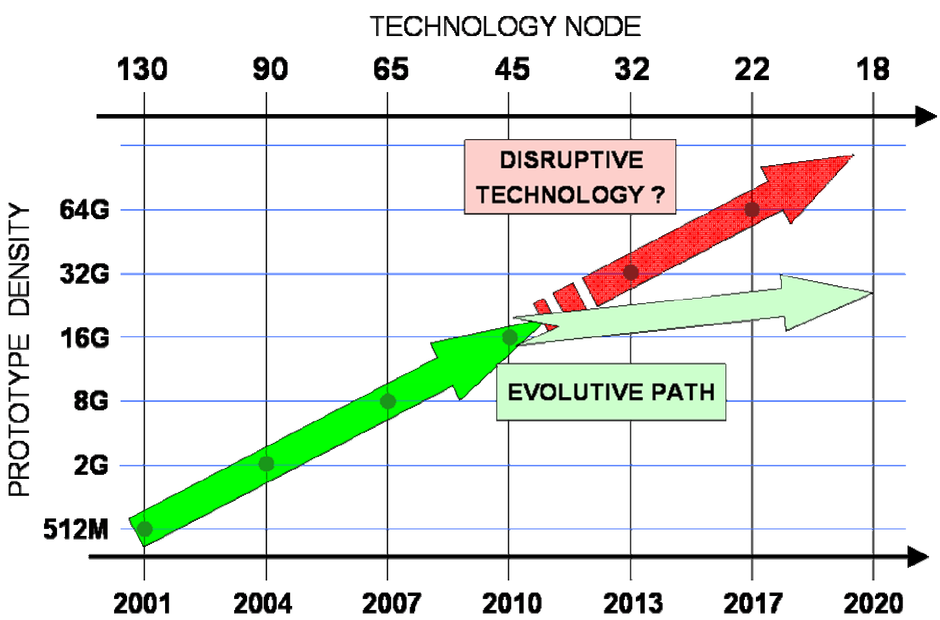


Figure 4.6: Prediction on the evolution of the density of solid state memories

Along the disruptive technology path: new approaches need to be investigated for the technology nodes beyond 45nm, taking into account that at least ten-fifteen years will be needed to go from the proof of concept of the storage mechanism, to the industrial exploitation. The most likely candidates will be storage mechanism based on resistivity changes in complex molecules (organic or not), but also polarization effects, like in ferro-electric polymers, or magnetic effects could be exploited. Multi layer storage technology is an important direction to reduce cost, and it is the most significant advantage of disruptive technology, but will require new reading mechanisms, and the development of new memory architectures, unexplored till now.

Two key considerations that should drive research activity are:

- the new approaches should address integration densities beyond the 16Gigabit, and address defectivity and reliability issues on this scale;
- the development and acceptance of new concepts, especially when reliability is a critical issue, as for long term storage, takes a long time. Therefore the new approaches must have a good scaling potential, not to be limited to a narrow temporal window.

It should be considered that the evolutionary approach will continue to be present (aided by powerful signal processing techniques, even if with reduced scaling potential and that all new technologies will have to measure against it and prove to have a significant competitive advantage.

In general three levels of research project can be envisaged:

- <u>Basic investigation of new storage mechanisms</u>: it should be performed in high risk, small size explorative projects, with a strong participation of Universities, demonstrating the properties of the material on single cells;
- <u>Investigation of integration properties</u> of the new memory concept: it should demonstrate that the storage mechanism can be integrated into a full memory, considering also the possible array architecture, programming and basic reliability performances, material compatibility with CMOS substrates. It should include also industrial partners, not only memory producer, but also providers of materials and deposition tools. The properties should be demonstrated at least on multi-megabit arrays.
- <u>The final proof of feasibility</u> for the new technology that should demonstrate its capability for realizing multigigabit memories, which are competitive with the evolutionary path. It should cover all the integration chain, from the assessment of the physics of the failure mechanisms, to a statistical evaluation of the properties on the gigabit scale, to the design aspects. A key element for the success of the project will be the ability to mobilize the critical mass of research and industrial resources, which are needed to overcome the entrance barrier, formed by the established technology.

The last step will be an essential part of any program on alternative approaches to mass-storage, and be the key to the success or the failure of the program. It is also the one that, in addition to industrial resources, will mobilize the largest amount of Universities and Research Centers.

In addition, it must not be forgotten that the memory is also one part, even if essential of the complete mass-storage system, therefore:

System level integration research should be initiated to provide technology platforms which enable to effectively integrate massive storage functionality in a wide variety of application areas. Especially in this area standards will be established based on which solid state memory functionality should be integrated in future designs.

4.2 Optical memories

4.2.1 Optical discs today

Optical disc storage is the most popular technology for storing and sharing audio, video and data. In 2003, the global sales of optical discs amounted 17 billion pieces, (11 billion with pre-recorded content and 6 billion recordable discs). Almost every personal computer contains an optical disc drive, and optical disc drives are popular for recording and playback of music and video. This business of a multibillion discs and half-a-billion drives annually has grown from a series of inventions done by Philips and Sony in the 70s. These two companies launched optical data storage products in the late 70s with the laser video-disc and the compact disc (CD). The compact disc was the first digital electronics product for the consumer. It became the media of choice for digital audio, and later also for software, video and data for PCs. The video version of the compact disc was in the mid-90s succeeded by the Digital Versatile Disc (DVD). Today's rate of acceptance of DVD into the homes of the consumers is spectacular and unprecedented. DVD players have taken over the lead in the market place of the VHS-tape recording systems.

Optical discs have become so popular because they combine the following key advantages:

- An optical disc is a low-cost publishing medium for the content industry,
- Increments of the capacity of collections of stored content also comes at a low-cost,
- Media may be exchanged between systems, because of well maintained, long-living global standards
- Discs may also be exchanged between users, also as a tangible gift
- Content can be removed from the reader for security / privacy and for archiving
- Customers can record their own discs.

Customers face an increasingly larger range of options for satisfying their storage needs. Also the volume of information to be stored is exploding. On top of that, digital content that users have becomes more and more personal and uniquely valuable (pre-recorded audio vs. digital pictures or movies taken at home). It is the aim of research on optical storage systems at various groups in Europe to continue to exploit the special advantages of optical discs at still higher performance and reliability.

Several companies, including Philips and Thomson, have announced a new format based on blue laser optics: Blu-ray Disc or BD. The BD-format allows storage capacities of over 25 GB on 12 cm diameter discs, with the option for doubling this amount in a double layer disc. Blu-ray Disc products are already on the market in small numbers. They are expected to start to sell in high volume in 2006. These new BD discs will distinguish themselves from DVDs by an increased capacity, that can be used for higher definition video, longer playing time, but also for enhanced interactivity.

Plasmon (UK) makes professional, truly write-once archiving systems for enterprises. They use cassettes filled with 13 cm-diameter optical discs for this. In 2004, Plasmon has successfully launched the Ultra Density Optical (UDO) disc-system in 2004, largely based on BD, with 30 GB capacity per cartridge. Plasmon has announced that it will grow from 30 GB per cartridge via 60 to 120 GB over the next four years to meet the growing storage need of its customers.

4.2.2 Three generations optical storage

The demand for storage capacities continues to grow, because of progress in hard disk capacities, the on-going digitalization of content, for instance via growing email traffic, and digital recording of still pictures and video. The most widely used optical storage system today is the Compact Disc with 0.65 Gbyte per disc. The fastest growing product is DVD with 4.5 to 9 Gbyte per disc, and the most advanced system is Blu-ray Disc. CD, DVD and BD can be seen as three generations of optical storage.

Each of these formats provides a complete family of read-only discs (ROM), rewritable discs (CD-RW, DVD+RW, BD-RE) and recordable (R) or write-once discs. Each of these modalities builds on results of world-wide research, with a special role for Europe. The ROM-discs have triggered research and development on laser cutting (or mastering) technologies, replication technogy, mainly injection moulding, and on copy-protection and digital rights managements. The rewritable discs have stimulated significant materials research on the doped-alloys of germanium, antimony and tellurium, the so-called phase-change materials. And the recordable discs contain a lot of know-how on dye materials and their processing.

Research in the coming years on optical disc systems could be directed towards improving the already developed generations of optical disc systems and to generate new options.

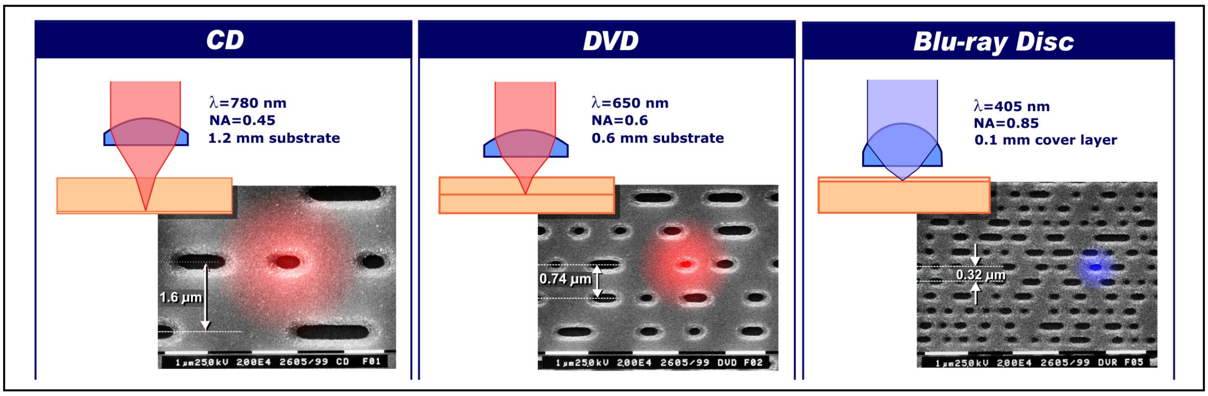


Figure 4.7 : Three generations of optical discs. With decreasing wavelength and increasing numerical aperture (NA) of the lens, the spot size becomes smaller. This can be used for reduction of spacing between tracks and marks on these tracks. In addition, the signal processing has become more powerful and tolerances have decreased in various parts of the system. This is a second reason for allowing a higher density of marks.

4.2.3 Improvements of CD, DVD and BD

The improvement of today's system is an active area of research and development at industrial laboratories. Part of these activities are directed to improving the intelligence of optical drives, for instance in dealing with optical discs that are damaged or out of specification. Also the speed at which recording can be done is under study. And there is continuous attention for cost reduction, for instance via integration of different optical or IC-components, or via doing more advanced signal processing to enable wider tolerances, or lower costs for media and drives.

There are differences between today's stages in the product life-cycle for the three types of optical discs (CD, DVD, and BD). The incremental improvement work has more or less finished for CD. CD-drives and discs are now already for some time a mass-manufactured product. The DVD-system has entered mass-market now and is starting to mature. Write-speed improvements for new DVD recorders will be completed in 2005. For Blu-ray Disc, we are still in an early phase: First products have come out, and still a lot of work needs to be done before this will become a low-priced mass-market product.

This evolutionary work is clearly very relevant research and development work. But we have doubts whether EU-funded research would be appropriate here. The work on DVD has entered a mature stage, where non-public know-how of companies is essential, and projects may typically be completed on relatively short timescales. And this type of work is also more and more competition sensitive, using proprietary information at companies and leading to results that will in general not be shared in the public domain.

The blue optical disc format BD is in an earlier phase, and perhaps cross-company projects could still have an impact here. Some work was already done in projects like the Eureka project BLUESPOT, with participation of Thomson, MPO and LETI.

There are also competing technologies, with similar claims on density and data rate as BD, like various magneto-optical super-resolution techniques. There have been several recent projects on this, like e.g. the MAMMOSIL project (with participation of Leti, Thomson, Toptica, MPO and the University of Exeter) as well as in-company projects at Philips. At this moment, we have to conclude that these approaches have lost ground in their competition against Blu-ray Disc phase change recording.

4.2.4 Next generations

There may be opportunities for joint projects between industry and institutes for the advancement of BD. But there are definitely more opportunities for collaborative work between academic and industrial laboratories on next generations of optical storage. Interesting fields of research are advanced signal processing, near field optical recording, holographic optical storage, advanced recording materials, optical card systems.

4.2.4.1 Advanced signal processing

Coding of information and signal processing have been at the basis of digital optical data storage. Nowadays signal processing may be used to widen the margins of the system, to increase the speed or the capacity. An interesting approach is two-dimensional coding, that was explored in the IST project TwoDOS. By arranging pits on a 2-dimensional lattice instead of a linear track, and by reading the information with multiple spot, the project team was able to read back information at twice the BD density (50 GB), and with 15 times the BD basic speed: 560 Mbps, a world record!

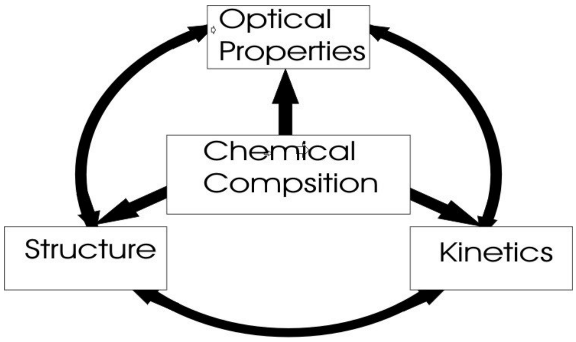
Figure 4.8: Logo of the TwoDOS project, with the consortium partners. The centre of the logo is a schematic view of a TwoDOS bit pattern.

Other work on signal processing concentrates at increasing the capacity of BD discs by adaptive decoding techniques. With various implementations of this technique it is possible to reconstruct data from marks that are so small that they can hardly be read by the optical system. This has allowed us to push the initial capacity on a BD disc of 23.3 or 25 GB to values well above 35 GB.

4.2.4.2 Advanced recording materials

With ever increasing demands to the materials for rewritable optical discs, the question can be asked here the limits will be. The group of Prof. Wuttig in Aachen is performing a systematic study of phase change materials to answer these questions. By heating these materials with controlled laser pulses, the materials can be switched between an amorphous and a crystalline state, each with their own reflectivity. Up to now, the development of phase change recording materials has been done via empirical optimization. The complexity of the interplay of the chemical composition, the amorphous and crystalline structure, their optical properties and the transition kinetics stress out the limitations of this approach and hence the need for a fundamental understanding to develop design rules for future phase change materials. Research could be done to acquire a fundamental understanding of the relevant structure – property relationships in phase change materials. Materials research can also help to improve the durability of optical discs to a level that is comparable to the 50 years guaranteed by Plasmon for their professional optical disc UDO.

Figure 4.9. A semi-transparent phase-change disc for multi-layer optical recording.



Fiure. 4.10: Schematic diagram by M. Wuttig for the interplay between structural, dynamical and optical properties of phase change materials.

4.2.4.3 Near-field optical recording

The BD system uses a laser with 405 nm wavelength, and a lens with a Numerical Aperture (NA) of 0.85. This leads to a resolution of about λ / NA. The resolution could be enhanced by going to shorter wavelength, or by increasing the Numerical Aperture. The technical challenges to this seemed so large in the past, that the BD-parameter combination of a just visible wavelength and the largest possible far-field NA, was referred to as marking the brick wall of optical recording. However, there is now experimental evidence, both from Philips and from Sony, that optical disc recorder technology with actuated lenses will be able to cross this brick-wall barrier, at least in the laboratory. And there is optimism about the feasibility of this technology in future commercial products.

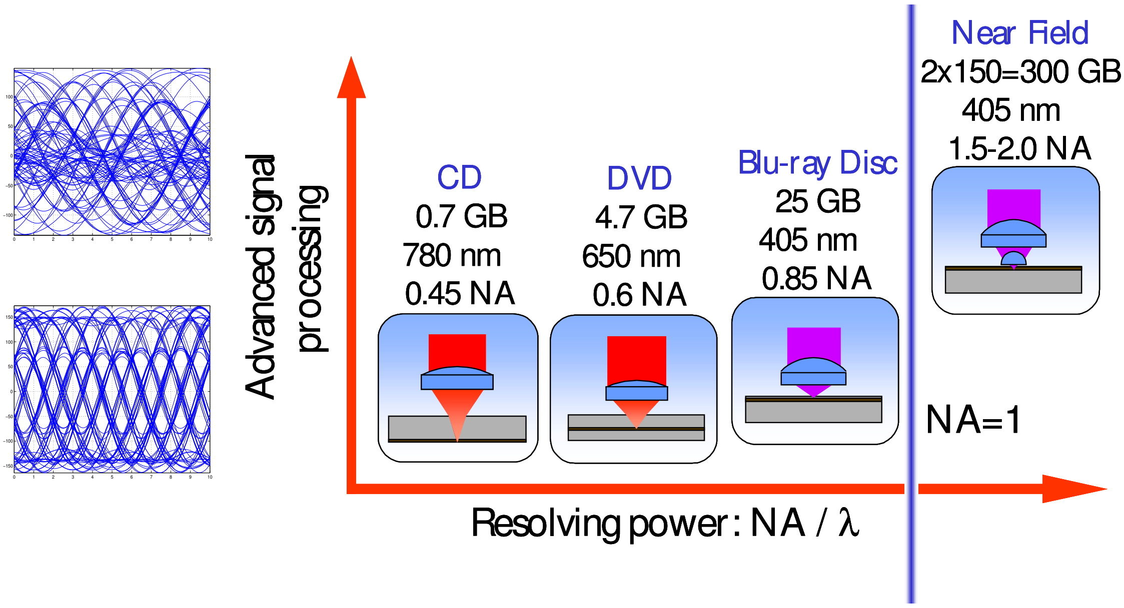


Figure 4.11: The brick wall of optical recording. For a wavelength of about 400 nm and a Numerical Aperture (NA) of 1, we leave a regime that has been exploited by CD, DVD and BD, and enter a new regime with new physical challenges in physics. This may be combined with advanced signal processing and coding techniques.

Reduction of the wavelength into the (deep) ultraviolet regime provides enormous research challenges for the solid state lasers and for the optical components (lenses, quarterwave plates, coverlayers, detectors). These could be topics for exploratory research projects. EU-funding could facilitate the forming of effective, cross-disciplinary consortia to execute these projects.

An NA above 1 leads to higher achievable densities. It also offers challenges, both conceptually and in practical construction of the system. The conceptual problem is that evanescent optical waves become important for these lenses. These evanescent waves die out when they are made to escape the lens. They are able to probe features on a disc only when the disc and the lens are very closely together. At such a sub-wavelength proximity, a rich variety in optical effects can be used to probe sub-wavelength features in the disc. Near-field optics has been a research topic in the IST project SLAM. The physics of this has not been completely understood and comprehensive modeling tools in this regime still need to be developed.

A practical problem associated to near-field optical storage is that the lens should be able to approach rotating, non-ideal plastic discs up to distances of well below 40 nm. This can be done via a slider, like in hard disc drives, and with an actuated system, like in CD, DVD and

BD drives. Both methods are being studied in the world. Philips and Sony have achieved nice recent results with actuators. The FAMOUS consortium (IST project with participation of a.o. the universities of Hanover and Cambridge, Thomson, Philips, Leti) has studied media for sliders.

With all these measures, near field recording systems can reach up to about a quarter of a Terabyte on a 12 cm optical disc, while being able to re-use to a large extent components, circuits and software that have been developed for Blu-ray Disc and its predecessors.

4.2.4.4 Optical multiplexing

A research consortium comprising of Imperial College London and the universities of Neuchâtel, Delft and Thessaloniki, has suggested the use of multiplexing techniques to increase the storage capacity. The idea is to store more bits of information in one location. This is not a novel solution: there have been experiments with storing additional information on discs by using pits with different shades of grey. However, these solutions all operate within a given (constant) space-bandwidth product and thus any gain in bandwidth is achieved by sacrificing signal to noise ratio. The solution put forward by the consortium is not based on "conventional" multiplexing but is utilising additional information hitherto left unmeasured. The method uses *asymmetrical* pits to encode data.

Because of the higher number of bits that are stored in one optical effect, the size of the effect itself does not necessarily need to be reduced to deep-submicron size. This means that the read-out of the high-density disc may be carried out at relatively modest values of the ratio NA/λ, thus avoiding the need to cross the brick-wall barrier from Fig. 11. The fine structure that is present in the effect assures the high spatial density.

Multiplexing may offer additional advantages in, for example data transfer rate. Multiplexing is naturally prone to burst error. But the consortium believes that that is not more so than BD or near-field solutions. Various multiplexing methods may be studied: Optical data storage, using far-field illumination and detection, could be based on colour-encoding of the information or via imposing various orbital angular momenta on the beams, or possibly a combination of these.

4.2.4.5 Holographic optical storage

Near-field recording or multiplexing techniques may take us to a quarter of a Terabyte on a 12 cm disc. If a terabyte or more would be needed on a single disc, then volumetric recording becomes an option that is worth studying. Holographic recording has been a dream in the optical storage field for a long time. Recent advances in polymeric materials and optical components like spatial light modulators have opened the way to make this dream a reality. Holographic data storage systems also hold opportunities for new signal processing, and perhaps even new storage and retrieval techniques. The page-based reading back of the information holds opportunities for a spectacular increase of the data rate.

4.2.4.6 Optical card systems

Instead of a race to ever higher capacities and data rates in optical recording, we may also look into other user benefits. As an example, research was started into optical card readers that do not need a spinning disc for reading back the information. Optical storage with parallel read-out and a minimal mechanical movement could result in much smaller readers, with lower costs, reduced power consumption and improved tolerance for shocks. There is room for revolutionary ideas in this type of research, and for cross-fertilization with other fields of storage physics and technology. Philips has published - as an example - on an optical card system at the 2003 IMST conference in Grenoble (Fig.).

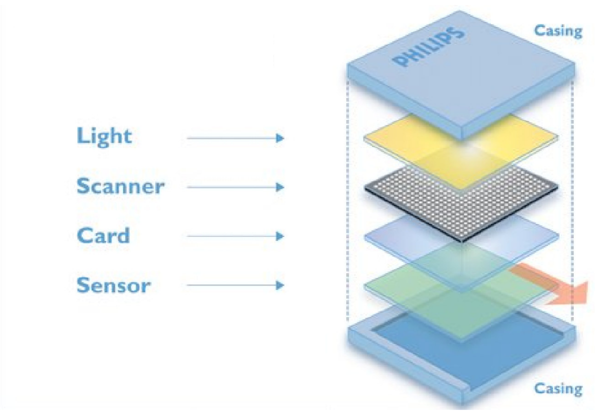


Figure 4.12: Philips proposed in 2003 a new optical card system that forms images of information of a replicated high-resolution card on a relatively low-resolution image sensor via an aperture array. The optical effect used for this is known as the Talbot effect.

4.3 Magnetic storage

The "School of Information Management and Systems" at University of Berkeley published in 2003 a comprehensive survey on the storage of digital information created in 2002 (How Much Information? 2003, at www.sims.berkeley.edu/research/projects/how-much-info-2003), following a previous survey published in 2000. The survey considers only 4 media: print, film, magnetic and optical (solid state memories discussed in this report still represented a very small total storage capacity in 2002). One trend shown in this survey directly interests this chapter: magnetic storage, already dominant in 2000, was still increasing its share in a market where the volume of new information rises at a rate of about 30% per year. About 92% of the recorded newly generated digital information was recorded on magnetic media in 2002.

And this year 2002 corresponded to a low for storage manufacturers, while results were much better in 2003. Citing the Magnetic Media Information Services (MMIS, at www.mmislueck.com/WhatsNews.htm), after two years of down *"all told 2003 was a year that rekindled hope in the hearts and minds of many producers and resellers of recording media of all kinds"* (this comment also includes optical recording media).

Along this track the total magnetic storage market is expected to reach about US$ 53 Billions in 2004. However this bright picture hides a very complex market in fast evolution, where different types of magnetic recording do not benefit equally from the global expansion.

4.3.1 Magnetic storage in its environment

Only a few years ago (e.g. circa 2000), the structure of the magnetic storage market looked rather simple:

- hard disk (HD) looked as the best compromise in terms of cost/bit, access speed and storage capacity, and was the main mass storage device in PCs and servers for everyday storage in office use.
- digital tape storage displayed the lowest cost/bit and the higher storage capacity, all the more that tape cartridges are removable and can be stored on shelf which somehow makes it a 3D storage. So it was the product one choice for backup and archival of large amount of data.

- tape storage also dominated the market of video recording (VHS in VCRs, camcorders) and of movie distribution to consumers.
- magneto-optical (MO) storage, usually more considered as optical storage, was used for data storage nearly only in Japan, but showed some expansion in other countries for rewritable mobile audio recording (minidisc).

This picture is being drastically changed

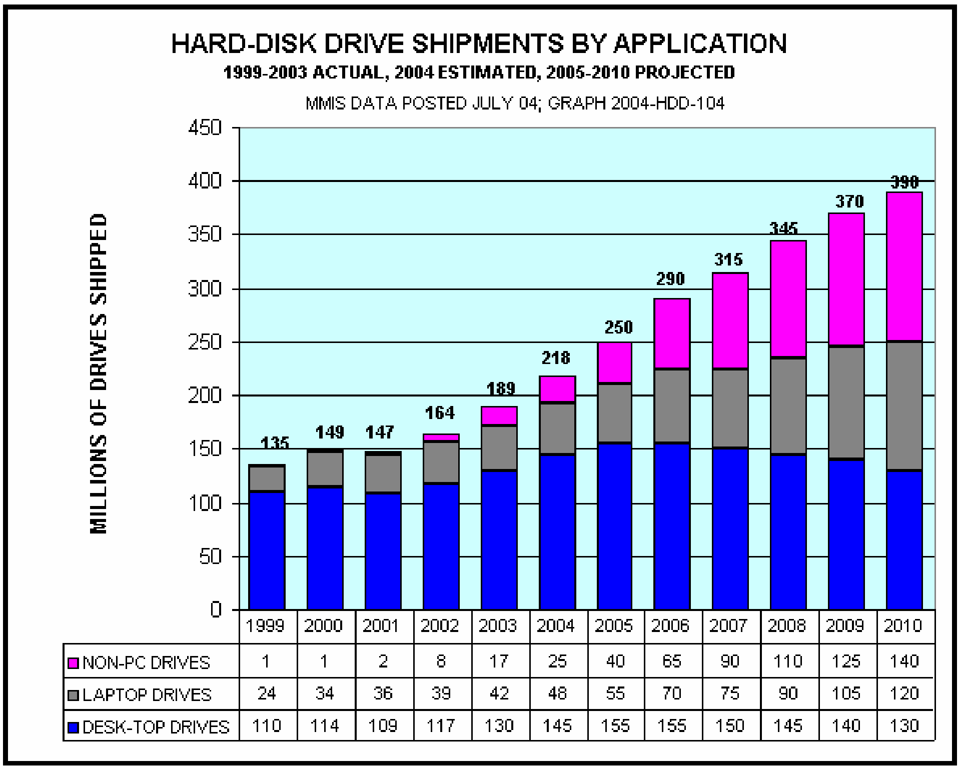
The trigger was probably pulled first by the very fast increase of HD recording areal density in the last 10 years. For instance, record values for commercial products increased from 1 Gb/in^2 in 1996 to 100 Gb/in^2 in 2004, i.e. a factor of 100 in about 8 years. This had major consequences.

First, desktop hard disk capacity (now up to 500 GB for Seagate's 3.5" in drive) has become very close to that of a state-of-the-art tape cartridge (circa 1 TB), while it shows much faster "random" access. So HD is now eating more and more on the market of back-up storage, with disk-to-disk storage solutions for primary backup, and disk-to-disk-to-tape for more long term archival of large amounts of data (for which tape retains a much lower cost/bit). More generally, professional storage is proposing increasingly complex solutions from redundant arrays of inexpensive disks (RAID) storage servers to storage libraries including HD, fast solid state disks (SSD) and tape. And it is more and more delocalized through network solutions such as Network Attached Storage (NAS), Storage Area Network (SAN), up to "Grid Storage" in the future. Storage software is crucial in such applications, to ensure reliability and easy data retrieval, and indeed the software market is expanding faster than its hardware equivalent. In words, the last years have replaced the traditional "storage" and "archival" by the concept of Information Lifecycle Management (ILM), that tries to organize the whole life of a piece of information from creation to long term archival.

Second, the areal density is now large enough to store many hours of video recordings (500 GB can store 400 hours of standard TV or 44 hours of HDTV!). This opened for HD the market of home digital video recorders (DVR), or more generally TV set top boxes, and even professional video recording for which the speed and random access of HD is a key asset. But this also allowed reaching quite high capacities in small form factors micro-HD (1.8 to 0.85 in), well adapted to the fast developing market of mobile storage in MP3 audio players (following Apple's iPod), digital still cameras (DSC), cell phones (first, HD based high-end phone by Samsung, Sept.2004), up to a consumer's camcorder integrating a 4GB microdrive (by JVC in Januray 2005).

So the years 2003-2004 could be named "hard disk years", when this so far PC-attached mass storage technology entered simultaneously the consumer's market and the backup storage area. This should open a bright future for HD recording, as appears on the previsions of HD shipments for different applications displayed on Figure 13 below.

Figure 4.13: Prediction of hard disk shipments by application, from "What's New from MMIS Newsdesk" @



	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
NON-PC DRIVES	1	1	2	8	17	25	40	65	90	110	125	140
LAPTOP DRIVES	24	34	36	39	42	48	55	70	75	90	105	120
DESK-TOP DRIVES	110	114	109	117	130	145	155	155	150	145	140	130

http://mmislueck.com/WhatsNews.htm, Sept. 29, 2004)

But other technologies also made fast progress. DVD for instance has nearly totally replaced VHS tape in movie distribution, and is now replacing it also for home video recording where for instance DVR combining HD and DVD-R/RW are expected to expand very fast in the next years, at least in developed countries.

On the other end of consumer's storage, Flash memories experience a capacity increase at a much faster rate than HD, and could well compete with micro-HD in a near future for high capacity (4 GB or more) mobile storage, while they have already conquered the sub-1GB range.

More generally, the magnetic storage industry, as others, suffers from a general production overcapacity, which results in a price war putting a strong pressure on hardware manufacturers. Hence an increase in drives shipment does not necessarily leads to an increase in profits, and this was particularly clear for HDD and magnetic media manufacturers in 2004.

4.3.2 Mainstream technologies

4.3.2.1 Hard disk storage

Technology and limitations

Areal recording density (in Gbit per square inch (psi) or Gbit/in^2) is indeed a useful criterion to evaluate hard disk technology. Figure 14 shows the evolution of areal density since the introduction of hard disk by IBM in 1957.

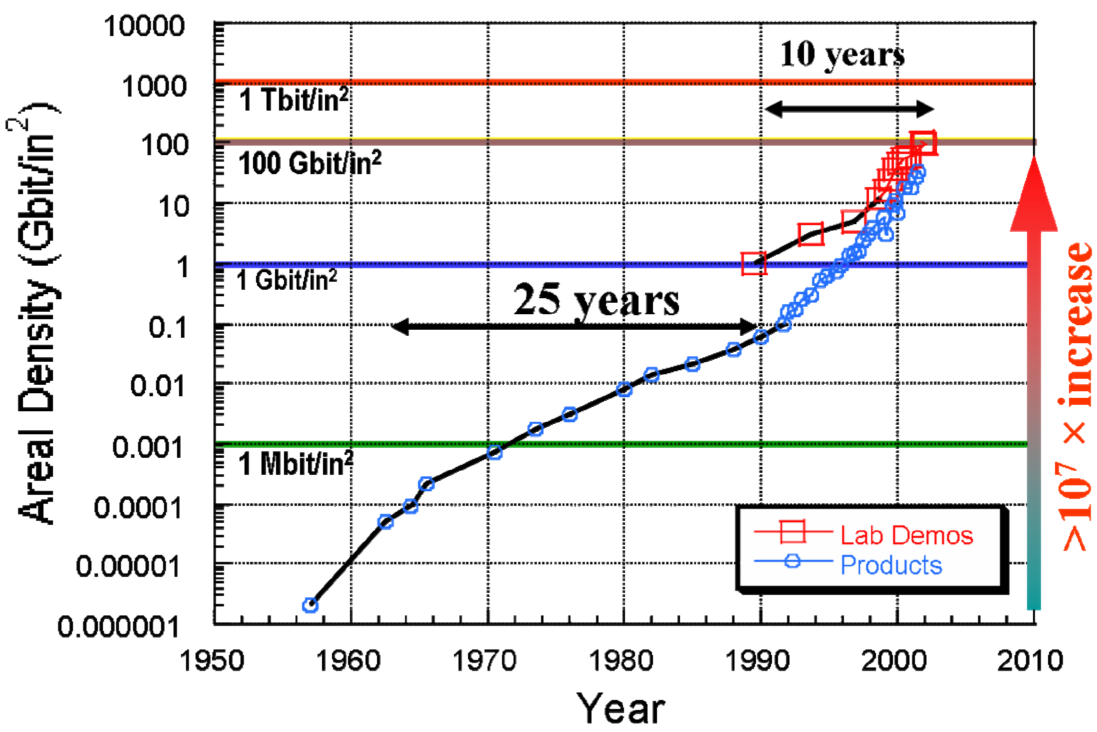


Figure 4.14: Evolution of the recording areal density for HD storage (© D. Weller,Seagate)

The trend is by far less stable than for instance Moore's law for semiconductors. This actually demonstrates that hard disk technology has been pushing its limits since its beginning. Each upward break in the curve corresponds to a technological breakthrough. The introductions of magnetoresistive head in 1991 and spin valve head in 1996 are at the origin of the drastic rise of the areal density growth rate up to more than 100% per year, with the remarkable effect on the hard disk market discussed above.

Here are some typical characteristics of hard disk technology in today's commercial products:

- the areal density in 2004 reached 108 Gbit/in^2 density (Seagate's 3.5in/500GB and 1in/5GB drives) for longitudinal recording.

- on the magnetic media, a 80 Gbit/in^2 areal density corresponds to a track pitch of 240 nm and a bit length of only 30 nm, so the 120 nm wide read element sense less than a hundred grains of diameter ~9 nm.
- disk rotation speed reached 15000 rpm in high end HD. This put pressure both on the head speed (Gbit/s is now nearly at hand) and on the tracking ability: the head must follow a 100nm track with relative speeds of the order of several tens of m/s.
- to keep spatial resolution and sensitivity the head flies at only 15nm above the media, to compare with contact separation evaluated at 10nm.
- Toshiba introduced a 0.85in HD with up to 4GB capacity, that weights less than 10g (cf picture on the right).

***Figure 4.15:* Toshiba 0.85-inch HDD with 2.0GB/4.0GB capacity**

But, as can be seen on Fig. 14, the very high areal density growth rate followed since 1997 puts tremendous pressure on research (products are now less than two years behind laboratory demonstrations), and so can no longer be sustained. Analysts predict for at least the next 5 years a more modest growth rate around or slightly below 50%/year. This is still quite high. For instance, the 1 Tbit/in^2 areal density, to be reached around 2010, will represent bit length of about 10nm for track width 64 nm. This cannot be obtained using today technology and certainly requires major breakthroughs and using new knowledge from Nanotechnology research.

Limits come now from trade offs between signal to noise, thermal stability and write ability, three factors linked to the media. Here how they come in.

- Magnetic recording today uses a granular media, obtained by co-depositing magnetic alloy and a spacer material such as Cr, SiO_2 or else C, that segregates between magnetic grains to cut the magnetic exchange interaction. So a limit between two recorded bits has to follow the grain boundaries, which makes it rough, and thus more difficult to detect. With today's numbers this effect dominates the signal to noise ratio. Hence grains should be smaller and more uniform in size for higher recording densities.
- Thermal stability describes the possibility that one grain spontaneously reverses its magnetization by thermal activation. It is usually characterized by the factor KV, where K is

the magnetic anisotropy constant of the grain and V its volume. To obtain 10 years stability of stored information KV must be greater than a factor that takes into account thermal energy and the very strong dipolar coupling between antiparallel grains in two neighbour bits. So decreasing the grain size requires not only increasing K but also narrowing the grain size distribution, as smaller grains would become highly unstable.

- But then increasing K increases the magnetic field for writing the bit, and writing heads have already reached some kind of a limit: we are then facing a major frustration, often referred to as the "superparamagnetic limit".

The evolution of conventional longitudinal recording (in plane magnetized media) goes on until now thanks to constant innovations, such as the use of Synthetic AntiFerromagnetic medias to decrease interbit dipolar coupling, that are not true breakthroughs but help extend the life of the current technology.

More drastic changes are expected sooner or later, often involving multidisciplinary nanotechnology research:

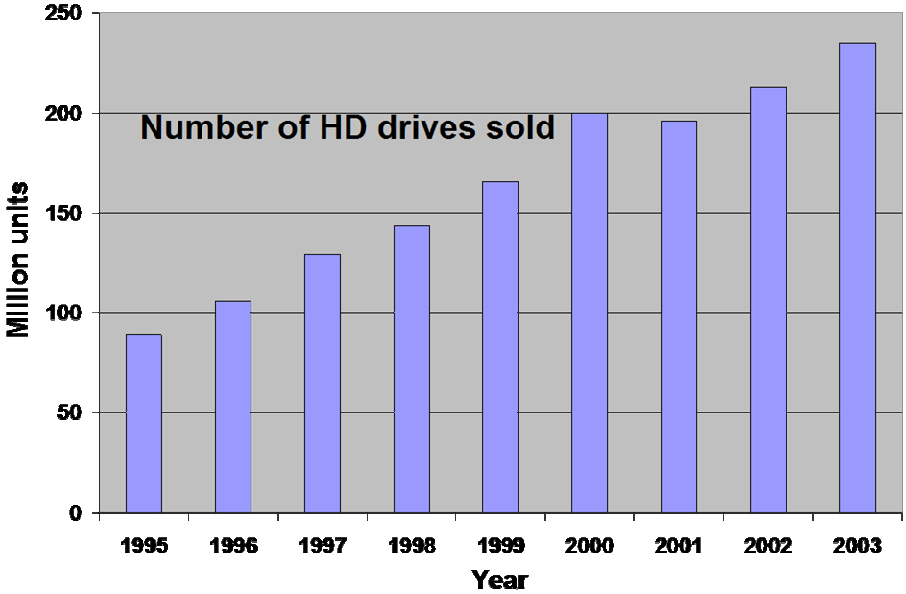
- a major breakthrough will be to change from longitudinal to perpendicular recording, which will both reduce the adverse effect of dipolar coupling on thermal stability, and allow to increase the writing field by a factor of 2 or 3. However, a new magnetic media is required with similar constraints on granularity, which furthermore includes a soft magnetic underlayer of stringent properties. And the head design is also more complex. *The shift from longitudinal to perpendicular has actually been announced by Toshiba in January 2005. The Japanese manufacturer plans to start mass production of 1.8in drives using this technology soon after April 2005. Areal density will then reach a record value of 133 Gb/in^{2}.*
- to reduce media noise by tightening dispersion in grain size and magnetic properties is a challenging objective. Although today's co-deposition techniques are constantly improving, major breakthroughs are expected from self organization techniques based for instance on chemistry.
- a drastic change could be to go from continuous to patterned media, where bits would be recorded on isolated grains arranged on a regular array. The one grain/one bit ratio would allow gaining at least one order of magnitude on areal density, and grain separation would help reduce dipolar coupling effects. However, 1 Tbit/in^2 density requires lithography with less than 12.5 nm resolution, which no ITRS roadmap is considering yet, and which would anyway be too expensive for mass production. So introduction of patterned media will require

disruptive mass patterning techniques such as nanoimprint (commercial tools already reach 30 nm resolution), or self organization techniques in multidisciplinary approaches.

- another major expected breakthrough will be the introduction of Heat Assisted Magnetic Recording (HAMR), where a laser pulse heats the media during a writing process to locally decrease magnetic anisotropy constant K and allow writing ultrahigh K media (FePt, CoPt ordered alloys for instance) with limited head field. Promising tests have been published using external laser beams, but the problem remains to bring the laser beam to the write head, and to localise the heat transmission to the media down to resolution well below standard light focus size. This last point will benefit from near field plasmon techniques. HD giant Seagate is actively promoting this approach, and shows confidence that "areal densities as high as $100Tb/in^2$ will eventually be possible using this technology" (cf "What's New from MMIS Newsdesk" @ http://mmislueck.com/WhatsNews.htm, July 24, 2004).
- for micromagnetic and sensitivity reasons today's current in plane spin valve head will not support size reduction well below 100 nm track width, and intense research aims at developing new magnetoresistive heads with enhanced sensitivity. Promising candidates use either current perpendicular to plane magnetoresistive heads, or magnetic tunnel junctions (comparable to the ones used in MRAM and discussed below). However, a head packs in a reduced volume several interacting magnetic structures that for instance tend to become magnetically "hard" when downsizing. So a major breakthrough would be to develop a non magnetic head, which would at least relax the micromagnetic problem.
- mechanics is a key factor in hard disk technology. One necessary improvement, already shown in demos, will be to include MEMS micro-actuators in the head to improve tracking. Beyond that, schemes are being proposed replacing the rotating disk by a probe storage technology (cf §2.4 of this report). A fully solid state solution for a "virtual HD" (a kind of magnetic Flash memory) could indeed be interesting, provided it can achieve similar high capacities and cost/bit as future HD. This would require some kind of 3D solid state device, as discussed in this chapter.
- error coding algorithm and advanced signal processing electronics with higher bandwidth, have become as important as magnetics to keep error within bounds.
- reducing power consumption would open new markets in mobile applications, where the micro HD already compete with Flash memory cards.

Status of the market

The total HD market has been estimated to about US$ 30B in 2003. However, such a figure depend very much on what is precisely included in the count. For comparisons, the OEM revenues on HD drives maybe a better figure, it has been estimated by IDC at US$ 16.3B in 2003, for 232°M drives shipped. Figure 13 above showed and estimated evolution of HD drives shipment for desktop, laptop and non-PC applications. Figure 16 below shows the



evolution of the number of HD drives sold annually since 1995. To give an order of magnitude, about as many hard disk drives were sold as TV sets in year 2000 (200 million units).Figure 1 above showed and estimated evolution of HD drives shipment for desktop, laptop and non-PC applications. Figure 4 below shows the evolution of the number of HD drives sold annually since 1995. More than 240million Units were sold in 2003 (Storage Newsletters, March 2004). To give an order of magnitude, about as many hard disk drives were sold as TV sets in year 2000 (200 million units).

Figure 4.16 : number of HD drives sold worldwide

With 100Tb/in^2 areal density expected to be achievable one day, it seems the capacity limit is no more an issue for the time being. However, the rate at which the areal density will grow in the near future will impact strongly the evolutions such as that shown in Figure 13, as this will determine the impact of HD on important markets where it competes with either tape storage on backup applications, or Flash memories on handheld devices (Flash memories capacity about doubles every year, but with also some limitations looming ahead, see the chapter on solid state memories).

So the evolution of hard disk puts high pressure on research, and in multidisciplinary areas. So the sales low in 2001 provoked some major restructuring in the industry. As a whole, hard disk industry is a very competitive industry where there is no room for too many players, and today only 7 major manufacturers remain: Seagate, Western Digital, Maxtor, Hitachi GST, Toshiba, Fujitsu et Samsung, and for heads only: TDK/Headway and Alps. . Cornice, a start-up launched in June 2003, seems to gain some speed on the micro-HD market.

But expanding hard disk industry has an important impact also on other manufacturers. HD has for instance quite a high content of electronic integrated circuits (IC), as schematized in Figure 17. The "ICs for HD" market was slightly above 3 B$ in 2003 (cf L. Baldi, ST Microelectronics), and is also expected to grow. Moreover, the need for ultra small hard disks for handheld devices gave rise to the introduction of the "storage element" (Cornice, 2004), i.e. a micro-drive without most of its control electronics. The control electronics is then included in the IC of the main device. On one side, this reduces the total IC share in the device final cost. On the other side, this may open some opportunity for leaders in HD controllers to attack new System-on-Chip (SoC) markets by using their specific HD expertise.

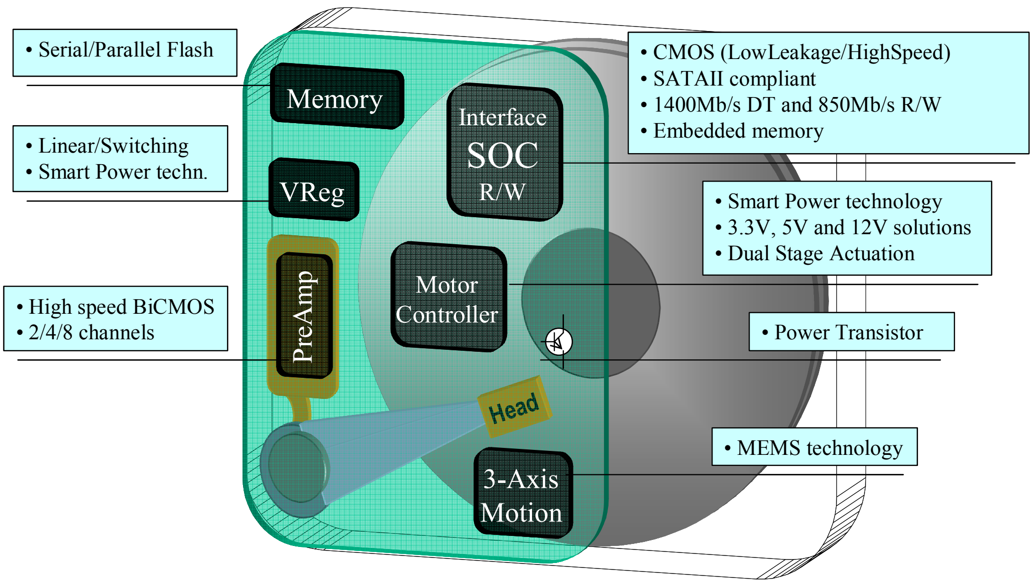


Figure 4.17: The IC content in a HD drive (from L. Baldi, ST Microelectronics)

The role of Europe

Seagate Northern Ireland remains the only real European direct player, after IBM sold its hard disk division to Hitachi and closed its Germany and Hungary plants.

However, ST Microelectronics and Infineon (with respectively 540 M$ (N°2 ranking) and 33 M$ market share in 2003) are important players in the field of ICs for HD, while for instance Singulus and Unaxis are leading manufacturers of thin film deposition equipment for this area (together with other optical data storage areas). Hence EU is still an important though indirect player in HD recording.

The desperate need for breakthroughs can also make a start-up very successful at securing intellectual property. If we consider the possibility that existing European companies may participate to future disruptive evolutions of the technology, then for instance:

- Nimbus (UK) or Obducat (Sweden) could take an important part in patterned media development by providing expertise and equipment for master masks fabrication and technology for nanoimprint,
- MPO (F), a manufacturer of optical discs, is now also considering nanoimprint.
- Nanomagnetics (UK) is studying self organized magnetic media for a range of applications including hard disk recording.
- Naomi technologies (D), a spin off of former IBM Mainz, proposes electronics and magnetic technology developments for recording, sensors, MEMS, etc…
- etc.

4.3.2.2 Tape Storage

As mentioned above, tape storage market is rapidly changing due to severe competition with hard disk and optical storage, even on its traditional backup storage market. However, according to most experts the expected decline of tape recording is not yet for tomorrow, as tape storage still holds some strong advantages for archival data storage and has a large margin for improvement, compared to other storage techniques.

Technology and limitations

Tape storage has a much lower areal density than hard disk, but compensates by an extremely large area of media in a comparable volume. For instance, when a hard disk drive can store 70 Gbits.in^2 but only on an area of a few in^2, tape has only 0.5 Gbit/in^2 areal density but on 10 000 in^2 total area. So tape products with more than 1 Tbyte/cartridge have come out in 2003. And tape is a removable media, so a large number of cartridges can be stored on shelves off site, making it a quasi 3D storage. Besides, the lower cost of cartridges compensates the somewhat higher cost of the drives. Mid term reliability is also supposed to be much better than for hard disks, the main competitor. These are the main reason for conserving tape as preferred data archival technique, more than a hypothetical very long term reliability that is limited by mechanical stability of media and tape (cf §3 below)

Access time being nearly impossible to improve (difficult to move tape faster), major improvements should come from data transfer rates and higher areal densities.

Data rate can be directly improved by using mutichanneling techniques. This is already achieved with enterprise quality standards such as LTO-2 with 8 channels read/written in parallel by arrays of head. As another example, the new EU-US company O-Mass is developing a mixed technology with magneto-optical reading that could follow up to 64 channels in parallel.

Higher areal densities with better signal-to-noise ratio could be obtained by using spin valve read heads. However, in tape recording the tape is moving in contact with the head, and spin valve heads are more sensitive to wear out at the tape-to-head interface than regular heads. Major improvements are thus needed in tribology also.

Moreover, reducing bit length and track width is made difficult by the mechanical problems linked to the fact that tape is a flexible support: dimensions fluctuate with temperature, humidity (tape "flubber"), precise tape guiding is also a problem that may strongly decrease reliability (cf Storage Magazine, March 2004), and controlling the winding is also important to avoid trapping bubbles etc… Magneto-optical read out can for instance offer extremely convenient tracking ability to help face those problems.

And the magnetic recording media is also deposited on an imperfect flexible support. Increasing areal storage density will definitely require to improve the magnetic media, going for instance from MP (metal particulate) media to ME (metal evaporated).

Finally, as in other recording technique, a lot is asked from advanced signal processing and error coding to improve the signal to noise ratio, if areal density goes up.

Status of the market

Tape storage is a rapidly changing market with many traditional areas declining.

In the domain of home applications, analog audio tape for instance is now limited to Asian markets, with only a niche market in US for recorded books. VHS video tape is already replaced by DVD for recorded films distribution, and should suffer more and more from competition with hard disk personal video recorder for time-shifting application, and DVD-R or RW for more long term video storage (at least in developed countries). Even in professional audio-video applications tape is being replaced by hard disk for digital storage and video editing. And, although JVC is producing the D-VHS, many analysts do not consider tape as a good candidate for future High Definition TV video recording, where hard disk and optical storage should share the market (see for instance MMIS, at www.mmislueck.com/WhatsNews.htm).

The situation is more complex for data recording, moreover divided in several segments (cf Fig. 18). Short term tape backup is being replaced by backup on hard disk, much faster for backup and recovery, and often done off site through networks. However hard disk backup is in most cases considered as a buffer to speed up the backup process, and a final backup will be made from disk to tape in a disk-to-disk-to-tape backup approach. Tape cartridges can then be stored off site for disaster backup. And tape backup storage is still much cheaper than 1 US$/Gbyte when hard disk backup can cost up to 10 US$/Gbyte. So tape data storage will go on, and predictions for 2004 expect recovery after several years of decline (cf Fig. 19) and throat cutting prices (cf also: www.storagesearch.com).

The size of the tape market is not easy to evaluate, all the more that it is splitted in many segments (cf Figure 18), and that systems associates media (~25%), drives (~36%), and automation. For comparison, 2003 estimation (IDC) gives US$ 5.7B OEM revenue for 37M tape drives shipped (HD drives: US$ 16.3B for 232M). Magnetic tape ex-factory revenue amounted to US$ 4.6B (MMIS). One expects also increases in shipped units for low end, mid range and high end products, but revenue will come mostly from high end and enterprise products (cf Fig 3). Besides, archival uses gradually shift from standalone backup to network backup, with a change from compact tape drives to more complex automated solutions.

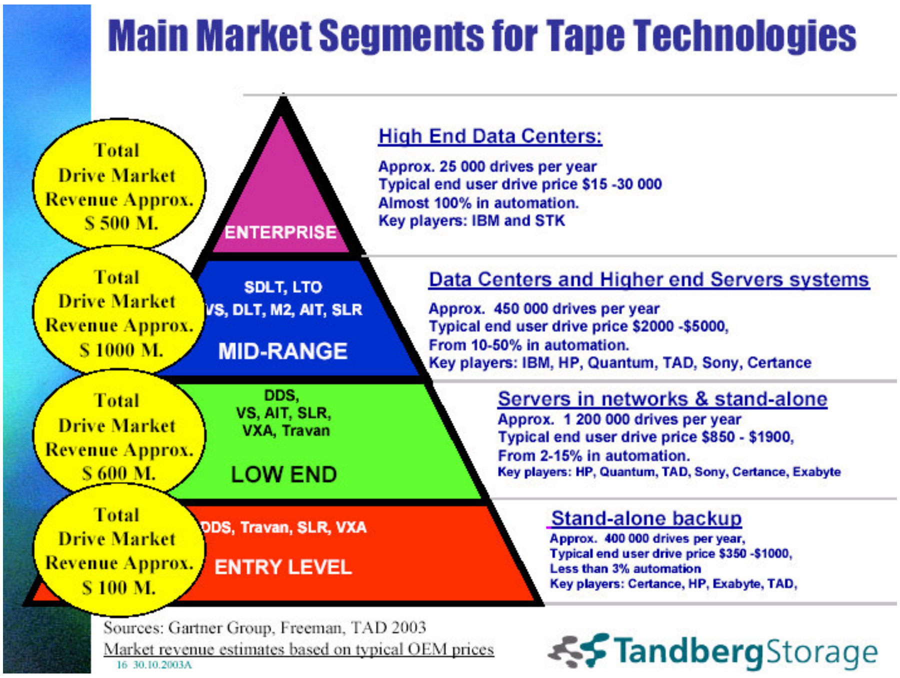
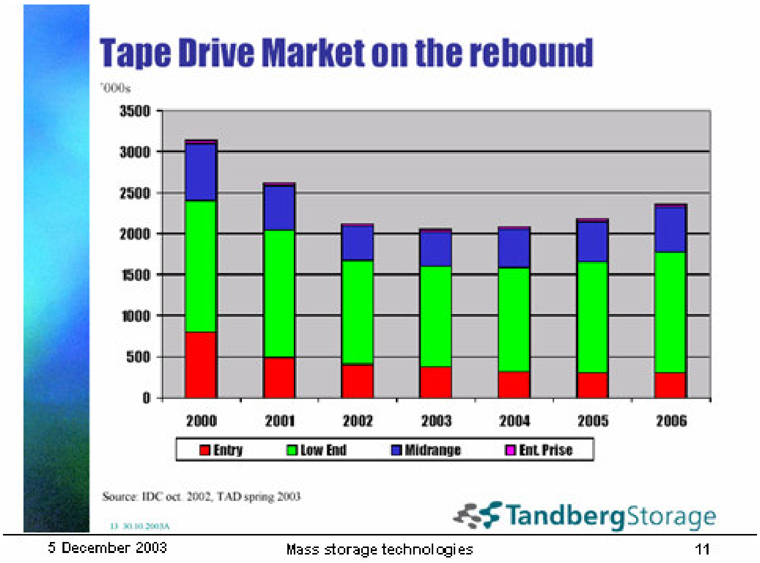


***Figure 4.18** (© Tandberg Storage)*

Figure 4.19

(© Tandberg Storage)



The role of Europe

The bankruptcy of European major EMTEC in 2003, one of the two largest producers of consumer audio and video tapes, reflects the rapidly changing nature of recording media market as described above. However tape industry remains active in EU despites severe restructuring in 2003.

Under pressure of a very competitive market, European major Tandberg transformed into Tandberg Data (integrated solution company), Tandberg Storage (hardware) and O-Mass, subsidiary of Tanberg Storage and Imation (30% share), a leading US company. O-Mass develops innovative solutions such as 64 channels recording with magnetooptical readout.

Naomi technologies (D), a spin off of former IBM Mainz, can also play a role in electronics, signal processing and heads development.

Many companies such as Storagetek France (F), Imation Germany (D), Hi-Stor (F), propose integrated backup systems that associate tape libraries with HD systems. Software is a key asset in such systems, and the storage software area is indeed in fast progressions, much faster than hardware. Such companies are strongly interested in what technological breakthroughs could bring to tape storage, as this could give them a leading edge for future developments.

4.3.2.3 Magneto-optical storage

Technology and limitations

Despites several advantages compared to purely optical recording, MO recording always suffered from a higher cost than other optical recording techniques, and could never overcome

hard disk in terms of areal density and speed. There however exist clear research synergies between MO recording and the new development of thermally assisted writing for hard disk technology, of HD perpendicular recording, and of MO tracking for tape recording.
In terms of evolution, a magnetic winning option for MO recording would be the introduction of the MAMMOS technology, by which nanosize magnetic dots can be written and read using micrometer size optical spot. This could become an option for optical recording beyond DVD & Blu-Ray technologies. But development of this technology is difficult. And at such high densities optical recording will have to go for near field options, and so could loose today's advantage of removability versus HD.

Status of the market

MO discs production totalled ex factory revenues of only US$ 330M in 2003, compared to US$ 2.3B for hard disk platters or US$ 4.6B for tape (MMIS News, January 2004).
Data storage accounts for only one third of this number, continuing a decline initiated in 2000 due to the competition with rewriteable CD and then DVD.
SONY audio MiniDisc makes up for the rest of the market. This technique is mostly successful in Japan (70% of the 7 M drives sold in 2003), with no sizeable US market but a fairly strong and once growing presence in EU. Beginning of 2004 SONY has shipped a new version with enhanced capacity (up to 13 hours of music), intended to compete with hard disk or Flash card operated MP3 players while retaining standard audio recording ability in any situation. However this MO technology keeps a higher cost, while the disk removability is no more a strong argument when latest increases in HD and Flash memory capacities give the new MP3 jukebox the possibility to store up to a hundred hours or more of music.

The role of Europe

Europe has long held a strong position in research with Philips and Thomson. However, Philips has stopped research on MO recording in 2002, despites technical successes in MAMMOS technology. For instance, the EU project MAMMOSIL gathered until recently industrial partners Thomson (D), Toptica (D), MPO (F), Unaxis, Nimbus (UK), research centre LETI (F) and academic Univ. of Exeter (UK), to develop MAMMOS technology.
MPO (F) is a leading producer of MO discs especially for minidisk.

4.3.2.4 Research opportunities in mainstream magnetic storage technologies

The need for storage will go on increasing in the IST, as *storage is becoming a critical element for future high technology development*. And magnetic storage occupies a central part in this area. As we discussed above, all magnetic technologies are now requiring major technological improvements and even breakthroughs, which puts increasing pressure on research. *Solutions will be linked more and more to multidisciplinary advances generated by Nanosciences and Nanotechnology research, where EU has a strong position*. So it is crucial to maintain a strong coordinated research on magnetic storage, and specifically HD, that would be closely integrated to the main stream of IST and Nanotechnology research.

Europe has high quality institutions such as INESC (P), Mesa Twente (NL), Spintec/LETI (F), Univ. Exeter (UK), Univ. Aston (UK), Univ. Hannover (D), etc. that are already leaders in magnetic storage research. And such a need for breakthroughs opens wide opportunities for research to develop and secure Intellectual Property. This can be done for instance through start-up companies. Research should also help existing European companies to regain or maintain a leadership position in the field, as technological advance will become more and more critical. Finally, a strong research seems the only mean to keep young scientists in Europe to work on this field.

So we believe that European Union should support research and development on magnetic storage. First step is to improve structuration to fight today's fragmentation and reach critical mass. This can be done on a global level, given the clear synergies that exist between the different types of storage. A Network of Excellence could be such a tool fulfilling both research and training requirements. For helping industry and start-ups on specific developments and innovations, STREPs would remain the key tool.

4.3.3 Emerging magnetic recording technology: magnetic random access memory

The interest for non volatile solid state storage was already presented in chapter §4.1, where Magnetic Random Access Memories (MRAM) technology is rapidly presented as one of several candidates for disruptive evolutions. But solid state mobile mass storage, today and tomorrow dominated by the Flash memory, is not the only area where can develop a non volatile solid state memory (NVM) which could compete in performances with other RAM memories such as DRAM and SRAM. For instance, energy savings could be huge if computers could be turned on and off within microseconds or less, without losing information.

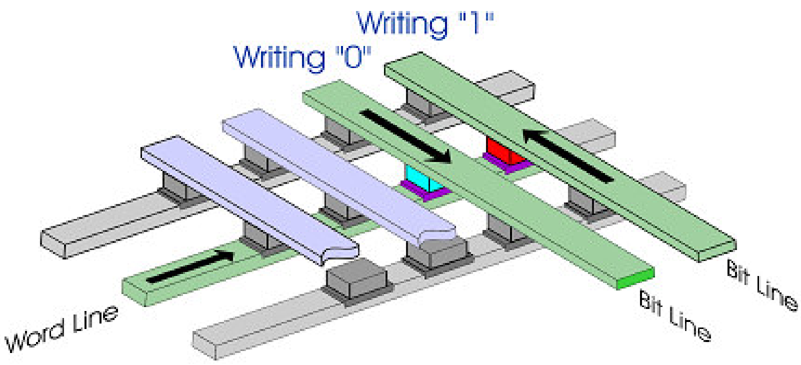
Bubble memories, introduced by Intel in the 80s but then rapidly dropped, was a first example of magnetic NVM that however had not the versatility to go beyond simple mass data storage. One step forward was the discovery in 1988 by European scientists of the giant magnetoresistance (GMR) of magnetic multilayers, followed by the practical implementation in 1995 of the magnetic tunnel junction (MTJ, modelled as early as 1975 by another European scientist). The MTJ was indeed the first magneto-electronic vertical device with the potential to be integrated into main stream high density MOS electronics. This started MRAM development.

MRAM have the potential to become as dense as DRAM, as fast as SRAM, added to non volatility and radiation hardness which are two known qualities of magnetic storage. However, usual trade-offs between thermal stability and write ability, already crucial in hard disk, add up with specific constraints of integration into mainstream semiconductor technology to determine future scalability. This will fix the exact fate of MRAM, from wide application to high density mass storage to restriction to embedded memories where the size requirements are less stringent. Hence innovative research is deeply needed.

Technology and limitations

Figure 4.20

(© S.S.P. Parkin, IBM)



In today's MRAM technology the binary information is stored on the orientation of the magnetization of the free layer F1 of a [F1/I/F2] MTJ stack, where I is a tunnel barrier (usually Al_2O_3) and F2 a magnetic layer whose magnetisation is pinned. The tunnel resistance of the device depends on the orientation of F1 through spin dependent tunnelling of charge carriers across I. Such MTJ cells are then placed at the cross-points of a dense array of perpendicular conducting lines, such as shown on figure 20. This is the standard *"cross-point"* architecture.

In conventional writing processes current pulses are sent through two perpendicular lines, and the resulting field can reverse the F1 magnetisation only at the line crossing. The intrinsic reversal process takes a few ns in the so-called "quasi static" mode, and can be much faster (below 200 ps) using fundamental properties of magnetization dynamics.

With today limited tunnel magnetoresistance amplitude ($\Delta R/R \sim 50\%$), the reading process requires that transistors be placed in series with each MTJ cell, to select the cell whose resistance needs to be measured. This architecture is called 1T/1MTJ and the corresponding cell is shown in Figure 21.

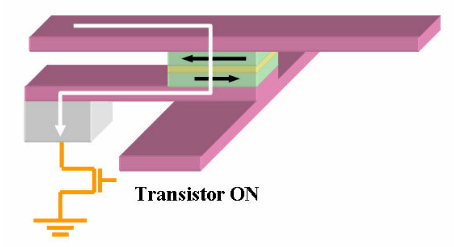
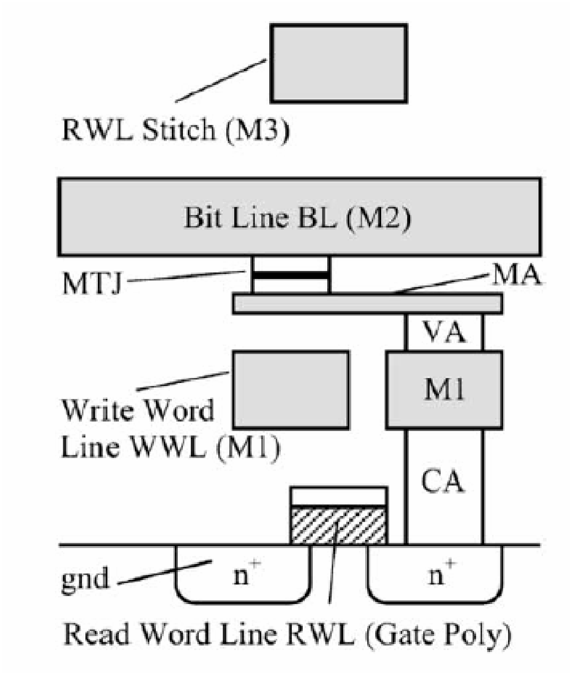
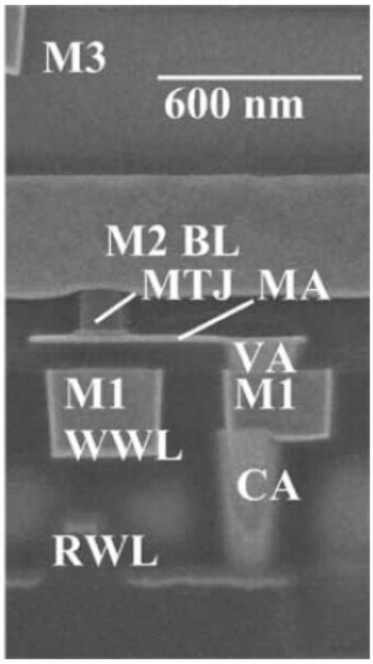


Figure 4.21

Finally, Figure 22 shows a scheme of the integration of the MTJ in the MOS technology, taken from the 128 kbits memory core demonstration presented in June 2003 by the Infineon/IBM consortium.





<u>Figure 4.22:</u> IBM/Infineon 128 kbits MRAM core (DeBrosse et al., IEEE J. of SSC 39, 678 (2004)). The RAM was realized in CMOS 0.18 µm technology, with a cell size ~43 F2 and Vdc = 1.8 V. Write/read times are around 5 ns.

One interesting observation is that the MTJ is made after completion of the MOS part (above metal level M1 in Fig. 22), and connected to it through vertical conducting vias. In terms of integration into MOS technology this may not raise too much the number of lithography levels (and so the fabrication cost), and is highly interesting for embedded memory applications. But it limit the high temperature back end annealing usual in MOS technology. In terms of mass storage, this may provide a substantial advantage if one can get rid of the read selection transistor and use the simple cross point architecture. One could ultimately pile up several layers of memory arrays such as the one on Figure 20, on top of a CMOS level that would contains the memory controller logic. Very high 3D-like storage capacities could then be achieved on a single chip.

As mentioned above several limitations need to be overcome, and among these:

- to be able to develop cross point architecture for mass storage requires first to strongly increase the tunnel magnetoresistance. A first step in this direction was made recently (Sept. 2004) by IBM (S. Parkin), and AIST Tsukuba (Y. Yuasa) with ANELVA, who simultaneously claimed tunnel magnetoresistances above 200% by replacing the Al_2O_3 barrier by MgO. Further increase will require new developments in materials, such as half metallic ferromagnetic metals (with 100% spin polarization), or new devices such as spin filters, where the non magnetic insulating barrier I is replaced by a ferromagnetic barrier where barrier height depends on the spin orientation of the tunnelling electron. Already promising results have been obtained, mostly by European laboratories, but the corresponding devices are not yet operational at room temperature.
- the writing process described above will suffer severe drawbacks at high densities. Electromigration controlled current densities in the word and bit lines will limit the achievable magnetic fields for writing, while the magnetic anisotropy of the F1 layer will have to be increased to ensure thermal stability. Also, cross talk between neighbouring lines and intercells dipolar coupling lines will start reducing write reliability (program errors) and thermal stability (non volatility). A lot of work is devoted to this issue, with several innovations such as the use of synthetic antiferromagnetic cells proposed by Freescale Semiconductors in its 4Mb demo (Sept. 2003).
- today tunnel barrier I is made of less than 1 nm thick of Al_2O_3, to reduce the resistance area product down to a level compatible with MOS technology. However resistance is still high and further thickness reduction would damage the reliability. So new oxides with lower barrier height are actively looked for. The MgO barrier would improve this point, if the recent results are confirmed.

As a whole, today's MRAM technology with some continuous improvements (cf below) are expected to hold for the next generations of MOS technology until the 65 nm node at least, and for the embedded memory application where ultra high densities are not a very strong prerequisite. For such embedded application the MRAM would benefit from its ease of integration, speed and cyclability, compared to competing NVM technologies such as Flash or PCRAM. Beyond that node, or for mass storage applications, major research breakthroughs are needed. For instance, two interesting ways of reducing the energy cost at writing have recently been presented:

- current induced magnetization switching (CIMS) would use the direct interaction between the magnetization and the spin of the conduction electrons injected through the MTJ. Proposed in 1996 by two US theoreticians, this "spin transfer" process has been demonstrated in 1999 on Co/Cu/Co pillars, and more recently on MTJ cells. Sub-ns speed were also recently demonstrated. Many patents have been taken on ways to reduce the energy cost of this method (tunnel barrier do not accept high current densities), and EU research has done some major contributions.
- thermally assisted switching (TAS) is derived from heat assisted recording in MO storage (or hard disk in the future). It would use Joule heating from a current injected through the MTJ to lower the F1 layer magnetic anisotropy during the writing process, which thus requires less energy. This process has been patented by European researchers (CEA Grenoble).

Finally, as for other magnetic recording technologies, advanced error coding algorithms are needed to ensure reliability.

Status of the market

There is no real market yet, as production is only expected to start by end of 2005 at best. However, to give an estimate, the market of logic components with embedded non volatile memories was about US$ 1.5B in 2004, and is expected to grow in the next years with the development of SoC ICs. Nearly all major semiconductor companies throughout the world are intensively competing to develop MRAM schemes, although some as Intel, HP or Samsung seem to privilege other techniques such as PCRAM or FeRAM.

Until recently, the most elaborate demonstrations were issued by:

- Freescale Semiconductors, that showed in September 2003 a 4 Mbit chip made in 0.18µm MOS technology, with bit cell size of 1.55 μm^2 and ~25ns access time.

- IBM-Infineon, that showed in June 2003 a 128 kbit chip made also in 0.18µm MOS technology, with bit cell size of 1.4 μm^2, access time of 5ns and a write pulse of 5ns. This 128kbit chip constituted the core of the 16 Mbit MRAM demonstration issued in June 2004 by Altis Semiconductors (an Infineon/IBM joint venture located in France). It seems designed more for embedded applications.

But major progresses were reported at the last IDEM Conference (San Francisco, Dec. 2004), were Asian manufacturers Nec-Toshiba, Renesas and TSMC reported new cells designs showing reduced cell size and operating currents. Renesas for instance designed a cell for high speed (>143 MHz) operation, while TSMC adpted its cell design for low energy operation. The Nec-Toshiba result could be even more interesting: a 1Mbit demo was presented, made in 130nm MOS technology with a cell design mixing 1T/1MTJ and cross-point architectures to reach $6F^2$ equivalent cell size, at the expense of a slightly slower access time (250 ns). This could prove to be an important step forward high density MRAMs for solid state magnetic mass storage.

As a comparison to evaluate how much progress still needs to be done, at 90-nm design rule cutting edge 6 transistors SRAM cells are about $1\mu m^2$, DRAM cells are in the 0.2 μm^2 range (~12 F^2), and NAND Flash cells around 0.045 μm^2 (~4 F^2). But one has to keep in mind that only 9 years have passed since first practical implementation of the MTJ in 1995. And the development phase started now will benefit from full support at state of the art semiconductor plants, and not only on R&D lines or in academic research.

Finally, the radiation hardness property of magnetism is already used in first generations of MRAM, produced by Honeywell using spin valve cells for space applications.

The role of Europe

Most important discoveries that led to MRAM came from European research. Unfortunately for a while development was exclusively made abroad, including the collaboration of Infineon with IBM which was pursued in IBM New York location.

Situation has now completely drastically improved:

- the MRAM technology optimised by the IBM-Infineon research team is now being developed in France by Altis Semiconductor, a jointly owned subsidiary, where a MRAM R&D Center is being set up at the 130nm/200mm Altis production plant.
- the implementation of the Freescale MRAM technology is now developed in France by the Crolles II Alliance (ST Microelectronics/Freescale/Philips), for production in the new 90nm/300mm Crolles plant near Grenoble.

- several start-ups have been created throughout Europe, to provide innovative developments in parallel with the R&D efforts in major companies (for instance Spintron and Crocus in France).

Besides, the European academic laboratories are still at the leading edge of research in this area, as are research centres such as INESC (P), LETI (F), IMEC (B, but more oriented towards semiconductor spintronics).

Research opportunities

As always when emerging technologies come to production, research opportunities are everywhere. And, as seldom in Europe, *research power and production potential are there too. So we believe there is a major opportunity that needs to be seized*. On the long term, only a very strong research effort of all partners will be able to retain today's industrial developments in Europe. It's only time, as in USA for instance research support organizations such as DARPA are already heavily funding research in this area, for both civil, space and military applications.

As usual, research effort is fragmented all over Europe, with local links between academic laboratories, research centres and industry. However, a long history of Research and Training Networks and Research Projects, in nanomagnetism, magnetoelectronic sensors, magnetic storage, etc., has already established many strong links between all partners.

So we propose to structure ERA first in at least two large projects, as was recently done for Nanoelectronics:

- a NoE mostly established between academic laboratories, and intended for structuring long term research, critical in this nanotechnology field to retain leadership. As exampled in other nanotechnologies areas, care will have to be taken to ensure some multidisciplinarity.
- an IP gathering all major MRAM companies, equipment companies, technological centres (INESC (P), LETI (F), IMEC (B), etc…), start-ups, and selected academic laboratories that are close to applications and would also serve as privileged links to the NoE.

In parallel, STREPs could help specific innovative developments outside the main stream. One was for instance started recently on "Magnetic Logic".

But MRAMs are only the first step towards a more systematic use of the spin of conduction electrons in what has been called "Spin Electronics". Recent fundamental research predict outstanding possibilities for a range of new designs with drastically reduced energy consumption and enhanced speeds up to several hundreds GHz. These emerging developments are validated by today's success in integrating magnetism into MOS technology. So a strong coordinated research on solid state magnetic storage, associating semiconductor companies, leading research institutions and academic laboratories, seems the required basis on which EU can build its future impact on Spin Electronics.

4.4 Emerging technologies for mass data storage

4.4.1 Introduction - Are new technologies necessary?

For the past fifteen years or so the IBM-type Personal Computer (PC) has been the dominant electronic platform in a wide range of everyday environments and for a plethora of applications (office-based tasks, e-mail, internet access, computer games, home-computing, data logging and analysis etc etc). Mobile, or ‘un-tethered’ (i.e. not connected to mains power supply) devices are now beginning to replace the PC in many areas and are likely to be the next dominant electronic platform. Examples of such un-tethered devices are already numerous and include laptop computers, personal digital assistants (PDAs), digital video and still cameras, personal music and video recorders/players, and mobile telephones. While computer sales are approaching 200 million units a year, mobile phones alone are expected to ship around 600 million units next year - reflecting the vital importance of the 'un-tethered' market. This change of dominant platform, from ‘tethered’ PC to a plethora of 'un-tethered' devices, naturally forces us to question the appropriateness for future applications of memory technologies developed for the PC-environment (e.g. SRAM, DRAM, flash memory, hard disk).

The change in dominant electronic platform is not the only reason for us to look anew at future storage technologies. The ever-increasing need for storage capacity has driven the density per unit area (areal density) at which data is stored ever-higher. In the hard-disk arena, particularly, the improvement in areal density has been phenomenal, as shown in Fig. 23. Most recently densities have doubled every year; a remarkable achievement brought about primarily due to the introduction of GMR (Giant Magneto-Resistance) readout heads. Such rapid improvements in the future are however much more problematic. This is primarily due to the now well-known super-paramagnetic limit (where ambient thermal energy is sufficient to reverse the recorded magnetisation). Overcoming the super-paramagnetic limit is currently a prime concern for the hard-disk industry, and many novel approaches are being considered. Of these, it is likely that perpendicular recording in high anisotropy media will extend densities to the 0.5 - 1 Tbit/sq.in. region, whereafter heat-assisted magnetic recording on ultra-high anisotropy media may well be necessary to provide further density gains. In light of this, INSIC in the USA is suggesting a density growth rate of around 30% per annum as a more realistic future proposition.

If we extend the IBM hard disk roadmap into the future by a couple of decades, whether a 100% or a 30% growth in density is achieved, it is not long before an individual bit on the surface of a disk needs to be of molecular or even atomic size. From such a perspective it therefore seems appropriate to look now at alternative approaches (to conventional optical, magnetic and solid state storage techniques) that do have reasonable prospects for nanoscale, and even molecular or atomic, surface storage.

We thus find ourselves at a critical point in the development of storage technology. Two very strong driving forces - a change in the dominant electronic platform on the one hand, and huge technical challenges faced by the storage mainstay of hard disk recording on the other hand - have generated the need for an urgent re-assessment of future storage possibilities. The time is ripe, therefore, to examine the question 'can and should new alternative memory technologies be developed to replace and/or compete with conventional approaches that have dominated the past?'

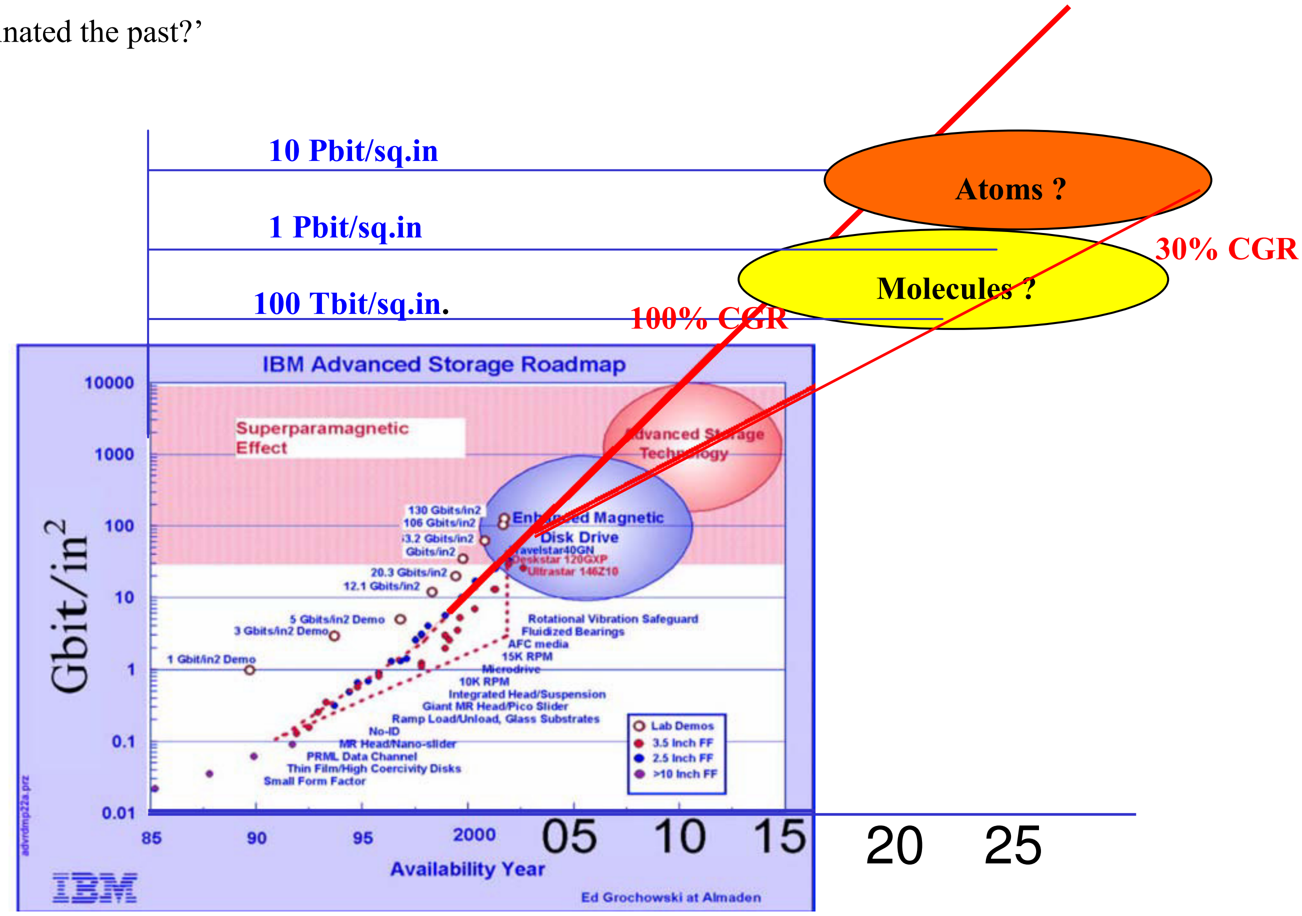


Fig 4.23: The IBM storage density roadmap extended to 2025. Two compound growth rates in density are shown; 100% CGR corresponds to growth rates achieved in recent years, 30% to the lower limit of what might be expected in the future in light of the super-paramagnetic limit and the need therefore to introduce perpendicular and maybe heat-assisted magnetic recording technologies.

In this respect we focus here on two areas (i) scanning probe-based storage and (ii) biologically inspired storage.

4.4.2 Scanning probe-based storage

4.4.2.1 Scanning-probe write and read processes

The field of scanning probe microscopy (SPM) has developed tremendously since the invention of the Scanning Tunnelling Microscope back in the 1980s. It is now practicable, for example, to use SPM technology to modify the surfaces of materials on the nanoscale, rather than just for microscopic imaging. Such surface modification might comprise the writing and reading of data, so providing a storage system with, ultimately, atomic resolution. Indeed, such atomic resolution was demonstrated in 1990 by Eigler and Schweizer, (Nature, 344, p524, 1990) who placed individual Xe atoms on single-crystal nickel substrate to spell out the IBM logo (atoms were on a regular grid 1.4 x 1.25 nm corresponding to the surface potential of Ni and gave an equivalent areal storage density of ~ 350 Tbits/sq.in.). However this approach, and similar atomic-level storage demonstrations by others, was exceedingly slow and, from a system perspective, offered an in-feasibly low data rate.

The probe storage field was of course given huge impetus by the impressive work at IBM (Zurich) into the Millipede system[1]. The Millipede concept is based on a thermo-mechanical writing process. A 2-D array of sharp silicon tips – held in place by cantilevers – is in contact with a polymer-based medium. To write bits, tips are heated above the polymer's glass transition temperature of and indent the media to form nano-scale pits. Reading is made through detection of the cantilever equilibrium temperature (thermal diffusion) versus local topography of the written medium, tips being insufficiently warm so as not to re-write to the medium. Impressive though the Millipede results undoubtedly are, the requirement for heating of the entire tip volume (typically of the order of cubic micrometres) to write a bit of nanometric size invariably means that power consumption is compromised. Indeed, the bit resolution in this approach is directly linked with the tip's sharpness. So this requires complex processes to sharpen the tips. However, the heat diffusion is limited by the tip's sharpness, i.e. bits will require higher power to be written if the tip is very sharp. Taken together, these

[1] The "Millipede"—Nanotechnology Entering Data Storage, P. Vettiger, G. Cross, M. Despont, U. Drechsler, U. Dürig, B. Gotsmann, W. Häberle, M. A. Lantz, H. E. Rothuizen, R. Stutz, and G. K. Binnig, IEEE Transactions on Nanotechnology, 1, **39** (2002).

factors imply that thermal recording has a limited scalability caused by a trade-off between resolution and power consumption.

A variation on the thermo-mechanical probe storage approach of IBM was investigated by Samsung/LG laboratories[2,] and by researchers at Shanghai Institute of Microsystems[123], who proposed a piezoelectric readout method that offered lower readout power consumption than the Millipede system. However, since the writing method was identical to IBMs approach, write power remained high.

HP have also recently announced a probe storage research programme based on a thermo-mechanical writing process similar to that proposed by IBM[4]. Readout is via a second order electrical effect. This HP interest follows on from their recent work on electron-beam based system (originally called Atomic Resolution Storage, ARS, although this acronymn is being carried forward to their new thermo-mechanical approach) where e-beam heating was used to induce phase changes in InSe/GaSe material to write bits – with readout being a form of EBIC (electron beam induced current). Unfortunately, this solution requires a relatively high voltage and vacuum packaging, which is not ideally suited to portable applications (and at the MRS Fall Meeting 2003 it was announced that this e-beam approach was being discontinued).

Probe storage based around magnetic storage media is also being investigated by various research groups, for example at Carnegie Mellon University[5]. As for hard disk recording, the density of magnetic-based probe storage is limited by the superparamagnetic effect. Writing can be achieved by applying a magnetic field, possibly assisted by heating of some kind[6,7]. Read-out can be performed by force-mode, as used in a Magnetic Force Microscope. This however requires a compliant cantilever and a sensitive force sensor, complicating the array design. Another option for read-out of magnetic bits is to use the magneto-resistance effect, as in a hard disk. This solution is power-hungry and complex (in its adaptation to a form suitable for probe storage).

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[2] Microcantilevers integrated with heaters and piezoelectric detectors for nano data-storage application, Caroline Sunyong Lee et al., Applied Physics Letters Vol 83, N. 23 8 Dec 2003

[3] Yano and Ikeda, Appl Phys Lett, 80, 1067, 2002

[4] http://www.hp.com/hpinfo/abouthp/iplicensing/ars.html

[5] Single-chip computers with microelectromechanical systems-based magnetic memory, L. R. Carley et al,,Journal of Applied Physics 87 (9) p 6680-5 (2000)

[6] Dependence of thermomagnetic mark size on applied STM voltage in Co-Pt multilayers Li Zhang, James A. Bain, J.-G. Zhu. IEEE Transactions on Magnetics, v 38, n 5 I, September, 2002, p 1895-1897

[7] Thermally assisted recording beyond traditional limits, H F Hamman et al, Appl Phys Lett, v 84, 2004

The electric counterpart of magnetic recording, ferroelectric storage, has been investigated for decades. This method is now being considered for probe storage[8]. Since contact writing can be used, very high densities over 1 TBit/in^2 can be obtained. The read-out mechanism is however rather complicated and not convenient for probe array integration, since it involves high frequency detection of minute changes in the storage medium's capacitance caused by the effect on the non-linear part of the permittivity tensor of reversal of the ferroelectric polarization. The method could in principle also be performed in non-contact mode, but at the cost of a reduction in data density.

Another category of probe storage might be termed 'electrical probe storage'. From a generic point of view, 'electrical probe storage' might be viewed as using an electrical potential applied to a probe that is in contact (or quasi contact) with a medium whose properties are altered in some way by the resulting flow of electrical current through the medium toward a counter electrode. The change in medium properties should be electrically detectable, e.g. by a change in electrical resistance. Several groups worldwide are pursuing such and electrically-based approach. Indeed, as part of an EU FP5 funded project (InProM, IST-2001-33065) researchers at CEA Grenoble (in collaboration with the Universities of Exeter and Twente) have developed a new type of scanning probe storage, that relies on an electro-thermal recording process in a phase-change material to provide an ultra-low power (<<1W), ultra-high density (1Tbit/sq.in. and beyond), ultra-compact storage system[89]. Figure 24 shows the basic record and readout mechanism of the InProM system. Experimentally recorded 20nm in a GeSbTe medium are also shown. Electrical probe recording as a generic approach has several attractions, in particular:

1) The **power consumption** for the writing process is low with respect to other technologies (0.1 nJ per written bit compared to Millipede's 10 nJ per bit). This is because only the dot memory volume, as opposed to the entire tip volume, is heated.

2) The **spatial resolution** obtained with electrical probe memory could be expected higher than in the "thermal" or "magnetic" approaches. This is due to a self-focusing effect of the current lines linked to the non-linear thermal and electrical responses of the media.

3) Considering that the **current** is obviously passing through the Hertzian contact area between tip and media, **the tip/media contact area could be very small** (for hard materials)

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8 Terabit inch−2 ferroelectric data storage using scanning nonlinear dielectric microscopy nanodomain engineering system, Y. Cho1, K Fujimoto, Y. Hiranaga, Y. Wagatsuma, A. Onoe, K Terabe and K. Kitamura, Nanotechnology **14**, 637 (2003).

9 C D Wright et al, Mat Res Soc Symp Proc, **803**, pp61-72, 2004

even if the tips themselves are not necessarily sharp. Indeed, the tip shape could be much 'smoother' than required by other probe storage modes, perhaps alleviating tips tribology and wear issues. There is also more flexibility in array design, since the role of the cantilever is minimal.

4) Electrical probe recording may also offer the potential for **true molecular-scale storage** - demonstrations of molecular-scale conductance transitions using STM tips have been made at Oak Ridge National Labs in the USA[9][10] (although interpretation of the physical mechanisms involved remains a point of debate).

In a recent and interesting development, a US start-up company, Nanochip (http://www.nanochip.com) has adopted electrical probe recording and phase-change media as the platform for and attempt to commercialise probe storage by 2006. Some $20 million of venture capital has been raised by Nanochip, and one of its supporters in Microsoft. It is believed that Nanochip is targetting all areas that NAND flash memory addresses today, and is aiming for 4GByte system by 2006 and 8GBytes by 2008 at a cost lower than half the manufacturing cost of NAND. Other examples of scanning probe-based storage abound, and are too numerous to mention in detail. Some notable approaches include charge storage in a nitride-oxide-silicon medium with a scanning capacitance microscope[11] , anodic oxidation of titanium with an AFM probe[12] , an AFM-based memory with polyimide Langmuir-Blodgett films[13], patterning of magnetic and organic films by 'Dip-Pen' nanolithography[14]. Indeed, researchers have studied a wide range of electrical, magnetic, thermal and mechanical effects (and combinations of these), in a wide range of media types (polymer, phase-change, ferroelectric, semiconductor, magnetic). It is also well-known that Seagate Research, Pittsburgh are actively investigating probe storage options - few details are emerging except that phase-change media are one of the options being studied see (http://www.seagate.com/newsinfo/newsroom/papers/D2c25.html)

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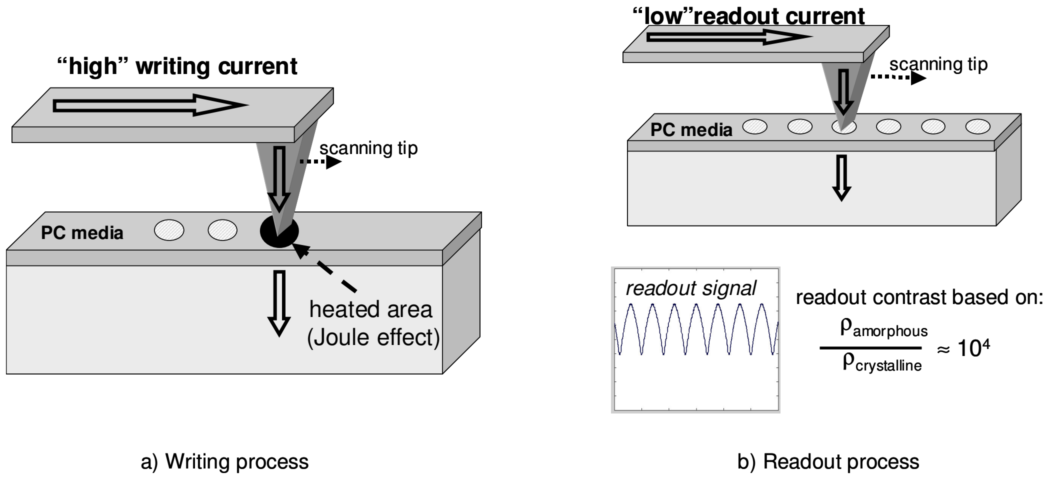
[10] H J Gao et al, Phys Rev Lett, 84, pp1780-1783, 2000
[11] Barrett and Quate, J Appl Phys, 70, 2725, 1991
[12] Cooper et al, Appl Phys Lett, 75, 3566, 1999
[13] Yano and Ikeda, Appl Phys Lett, 80, 1067, 2002
[14] Ginger et al, Angew. Chem. Int Ed, 43, 30-45, 2004



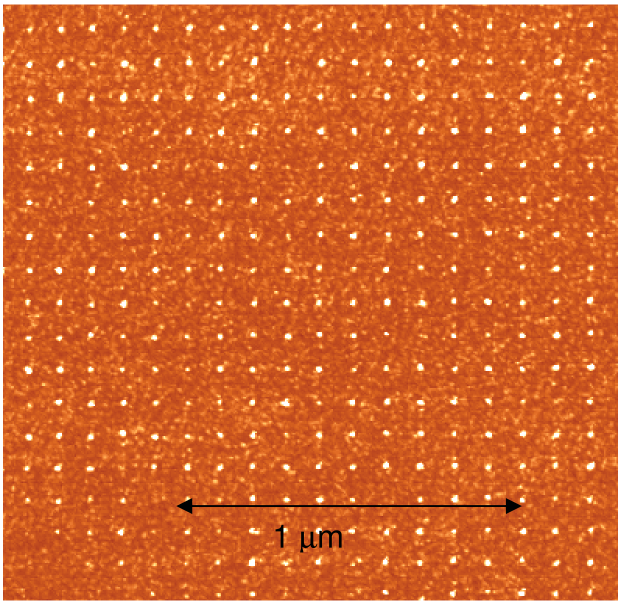


Fig. 4.24 Schematic of the electro-thermal scanning probe storage system using phase-change media. High writing current induces crystallisation by Joule heating (top left). Readout process uses much lower current to sense the different electrical conductivities of amorphous and crystalline phases (top right)

Experimentally achieved 20nm crystalline bits (left) written into an amorphous GeSbTe layer. In this image each mark is spaced 100nm from the next, leading to a storage density of 300 Gbits/sq.in. Reducing mark spacing to 40nm (i.e. 20nm 'marks' with 20nm 'spaces') would yield a density of 1.5 Tbit/sq.in.

Image courtesy of Serge Gidon, Olivier Bichet and Yves Samson, LETI-CEA

Scanning-probe systems aspects and performance

The immediate plans of commercial ventures into probe recording, such as by Nanochip, IBM and HP, appear to be targetting memory markets traditionally addressed by Flash NAND and perhaps the micro-hard drives. Probable system performance and design parameters for this application might be as shown in Table 3.

In the longer term however we envisage two main routes for probe storage development:

1) Towards very high density in a small volume (chip component type)

2) Towards huge capacity for mass information archiving in larger formats

A probe storage roadmap might therefore have two essential routes for the future, as shown in Fig. 25. The requirement for ultra-high capacity arises from the well known evolution of demand in data archiving (video, collective database, telecommunication systems,…), huge capacities in a reasonably useful volume, as in our now day life with DVD discs or tapes format, will constitute an interesting market. This one could be addressed by probe techniques transposed to disc or tape format, or some other large-media form factor. Tremendous capacity could be obtained. As an example on a CD format (12 cm diameter), we can expect more than one TB capacity, considering the conservative density of "Millipede" state of the art (0.2Tbpc).

Specification	**First Generation (2006)**	**Future Generation (2010)**
Capacity (GByte)	4	20
Data Rate (Mbit/s)	20	1120
Seek time (ms)	1.2	1
Peak power (mW)	100	100
Stand by power per tip(nW)	10	1
Density (Tbit/sq.in.)	0.3	1
Tip array size	32x32	128x128

Table 4.3: Probable probe memory system parameters for Flash-type applications

Grouping probe storage into two families then

- first products in small size chip
- mature products with larger chip

we might therefore identify various generations, each requiring technological breakthroughs in array/media/system design. Possible futures are illustrated in Fig. 26.

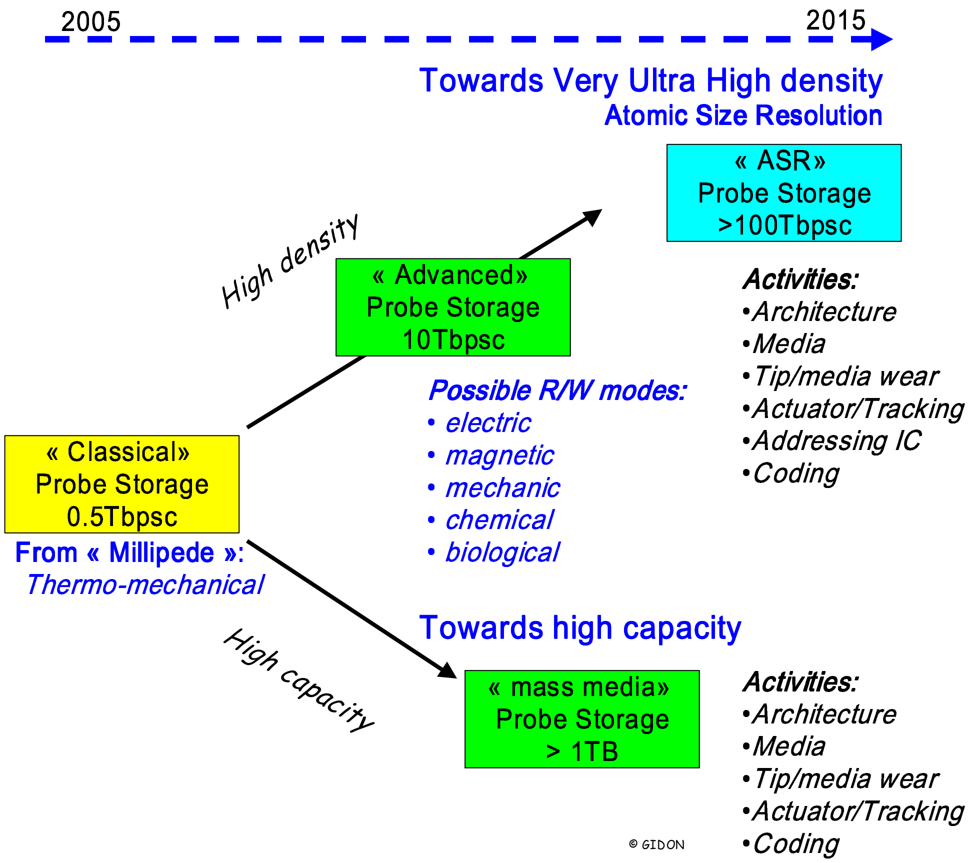


Figure 4.25 : High density and high capacity routes for probe storage (Tbpsc = Tera bit per square centimeter; TB = Tera Byte)

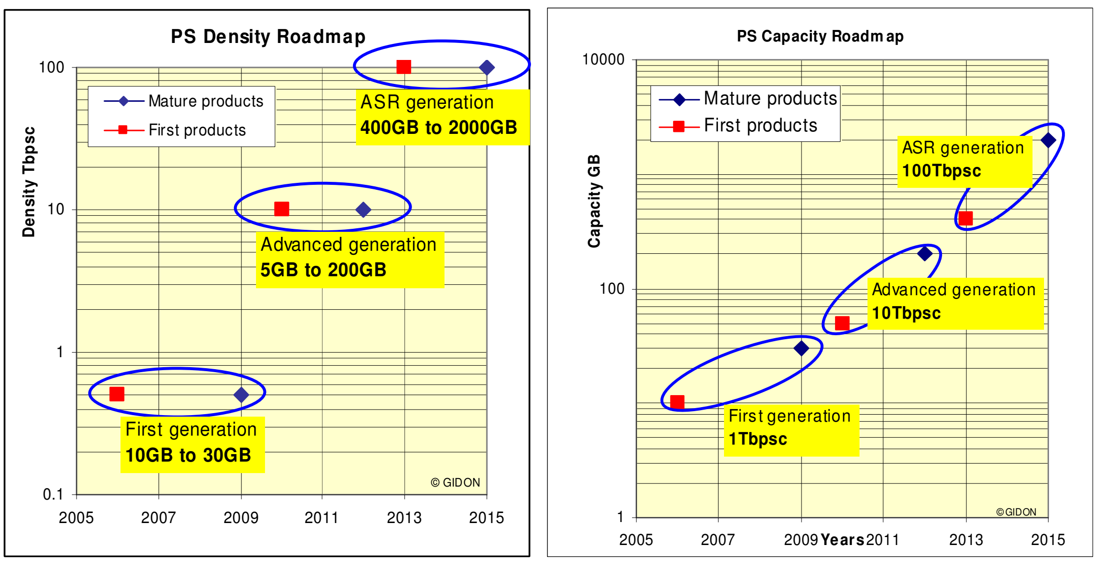


Figure 4.26 : Possible probe storage roadmaps for density (left) and capacity (right), showing various generations such as
2006: first demo (0.5Tbpsc -5 to 10GB)
2009: mature design (0.5Tbpsc -20 to 30GB)
2010: "advanced" probe storage on small chip size (10Tbpsc - 50GB)
2012: mature "advanced" probe storage (10Tbpsc - 200GB)
2013 "Atomic Size Resolution" on small chip size (100Tbpsc - 400GB)
2015 mature "Atomic Size Resolution" (100Tbpsc - 2TB)

Scanning-probe memory application areas

The potential performance advantages of probe storage mean that it is expected to impact on many application areas, some of which are described below.

Portable devices: The most important application of probe memories is, as already discussed, expected to be in the portable devices sector. Indeed, probe memories have the high data storage density and low power consumption essential to nomadic devices. Currently, flash memories are expected to be the standard solution for portable devices. However, flash uses a CMOS architecture, which aims at following the Moore's law and is not expected to reach the 50 nm node before 2009 (according to the ITRS Roadmap - see the following table). Incremental innovation on CMOS technology is very expensive and uncertain. ***Probe storage*** has the distinct advantage that it ***is not lithography limited -*** the bit size does not depend on lithographic resolution.

Cache memories[15,16] *:* Although they are not competitive with the access time of specifically design cache technologies (SRAM, DRAM, MRAM, …), specific probe memories can have a competitive access time regarding magnetic hard drives' (down to 1 ms, whereas state-of-the-art hard disks, turning at 15 000 RPM, reach 3 ms and are bulky) and are much less expensive than cache memories. This **low-cost intermediary access time performance**, coupled with **huge data capacity**, can greatly profit mass storage under heavy traffic (**improvement of system performances by a factor of 3.3 to 8.2**) such as massive server storage for online or enterprise use, or grid computing (supercomputers, clusters).

Raid architectures[17,18]*:* Another possible architecture using probe storage would be to realise a RAID array of probe recording modules. One could mount tens of chips in the volume of a 3.5" hard disk casing. Probe recording already has the option for a very short access time, in a RAID geometry the performance could even be enhanced. Such a module would be desirable in server applications.

Single chip computers[5]**:** Probe storage also has the potential to provide IC-based mass storage that might be integrated on-chip with traditional CPU, RAM and interface devices to provide powerful single-chip computers. Current-day so-called single chip computers do not have this

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15 Exploring the Usage of MEMS-based Storage as Metadata Storage and Disk Cache in Storage Hierarchy, Bo Hong, 2nd USENIX Conference on File and Storage Technologies (April 2003).

16 Using MEMS Device as Disk Write Buffer, Feng Wang, Scott Brandt, 2nd USENIX Conference on File and Storage Technologies (April 2003).

17 Using MEMS-based storage in disk arrays, Mustafa Uysal, Arif Merchant, Guillermo A. Alvarez, FAST '03: 2nd USENIX Conference on File and Storage Technologies (April 2003).

18 D. Patterson, G. Gibson, R. Katz, A case for redundant arrays of inexpensive disks (RAID), in: Proceedings of the ACM SIGMOD, International Conference on Management of Data, 1988, pp. 109–116

all important integrated mass storage capability. The use of probe storage might however allow us to integrate on same chip many GBytes of non-volatile mass storage with powerful processor and communications blocks. Such ideas have already attracted interest, primarily from Carley et al[5] at CMU Pittsburgh's Center for Highly Integrated Information Processing and Storage Systems. They imagine, for example, a low-power, single chip computer having >500MIPS processor, >64MB RAM, > 1GB non-volatile probe-based mass memory, >100MB/s communications. Such a development would go a long way to realising the 'ambient intelligence' necessary for our future technologically oriented society.

4.4.3 Biologically-inspired data storage

Biologically-inspired computing and associated technology has generated much interest in recent years. Naturally the interest is using biologically-derived mechanisms for data storage applications has also been strong. A common theme in this area is the use of DNA sequences for storage. A typical example is that suggested by Mansuripur in the USA[19]. In this approach, base sequences of G, C, A, and T bases are added to a growing DNA molecule (see Fig. 27), with binary or other data encoded in the order of such nucleotides (a quaternary data scheme might match best to this basic quaternary system). Data is read by an electrophoretic mechanism, where DNA molecules are brought from a 'parking' station on a chip to a nanopore through which they pass, thereby modifying an electrical current flowing across the pore. Writing occurs by chemical attachment of an appropriate base (G,C,A, or T) from a reservoir.

[19] M. Mansuripur, SPIE Proc, 4342, 1-29, 2002

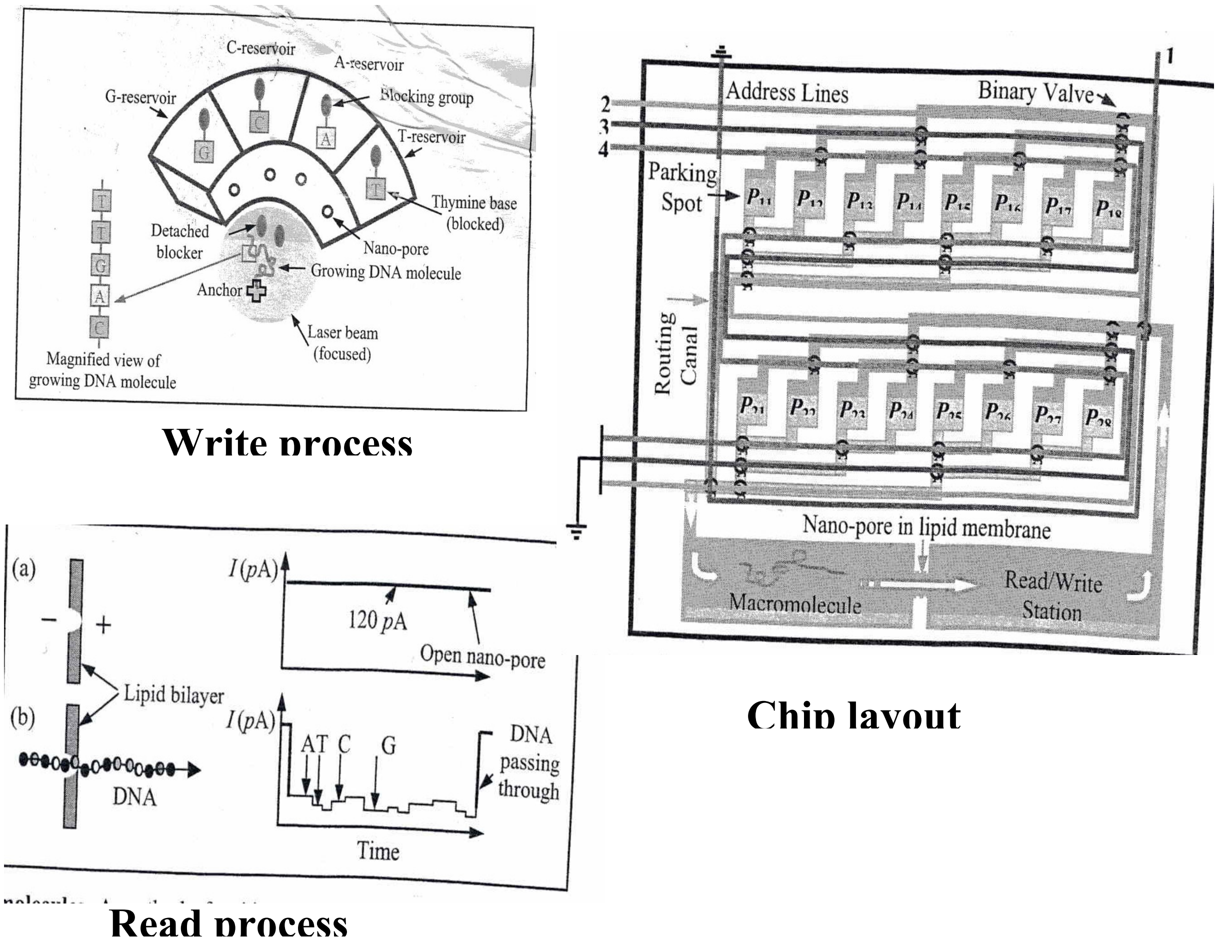


Figure 4.27 : A possible DNA storage scheme.

Although such schemes are superficially attractive and hold the promise of very high storage capacities, at present the processes by which writing, reading and transport around an appropriate chip architecture are achieved are far from reliable, lacking suitable sensitivity, selectivity and speed. Thus, it is not expected that such approaches will have any serious commercial application except perhaps in the very long time scale (> 15 years).

4.4.4 The role of Europe

Data storage technology is currently at a most exciting and critical point in its development path. To quote Dr Mark Kryder, Senior Vice President at Seagate Research, 'somewhere in the not too distant future we are going to have to change technologies to keep going forward'. Such a change of technology is necessary for two main reasons:

Technical challenges facing conventional hard disk recording arising from the super-paramagnetic effect, coupled with the inability (in anything like its current form) for hard disk recording to write and read data on the truly nanometric scale.

A shift in dominant electronic platforms away from 'tethered' to 'un-tethered' systems, requiring ultra-compact, ultra-low power, high capacity storage.

Indeed, this latter point has quite far reaching implications and is likely, as discussed in the Gilder Technology Report (vol IX, no 3, March 2003) to 'require a new component set, consisting of non-volatile PLDs, non-volatile memory and MEMS-based storage'.

A sensible and potentially successful route for Europe would be thus to target the development of high capacity, ultra-low-power, compact data storage formats for the burgeoning 'un-tethered', or mobile, technology market. Of the technologies suited to such applications, MEMS-based mass storage using scanning probe techniques offers perhaps the most attractive solution, from both a technical point of view and from an 'existing EU-strengths' point of view. On this latter point we can of course claim for Europe the invention of the scanning probe microscope itself, and the subsequent generation of a large and vibrant scanning probe microscope community. The MEMS community in the EU is also strong, and this forms a vital part of the process of adapting scanning probe microscopy architecture to produce a viable data storage system. Novel work on recording and readout processes suitable for use in probe-array systems has also already been supported by the EU and provides a strong base on which to build. There is also a strong argument in favour of concentrating on a new technology area in which we can compete globally and, if research and development is successful, establish new storage companies or support and extend the portfolios of existing EU industries. Furthermore, by targeting a technology with a relatively long time scale before introduction to the market (say 5 to 10 years time), the EU will be able to take maximum advantage of possible opportunities that investment makes available to it.

In summary then, we believe that, as far as 'emerging technologies' are concerned, the EU is best-placed to concentrate its investment in the development of scanning probe-based memory systems. There are numerous areas of scientific and technological endeavour that are required if such developments are to be successful, some of which are listed in Fig. 28. The aim must be to develop materials and systems to enable high density, high writing and reading speeds, low error rates (good SNR), longevity (of tips and media), high cyclability (for re-writable approaches), suitability for incorporation into a 2-D tip array, relatively low-cost fabrication. Research should progress on material alternatives (e.g. for write-once, re-writable) and systems (MEMS for actuation, tip arrays etc) simultaneously, such that a preferred and complete material/system combination can be brought together in a demonstrator or prototype in the medium term. Thus, there is a need for (i) basic investigations of storage mechanisms, (ii) development of new MEMS concepts (suitable for scanning probe memories), (iii) investigation of integration aspects, (iv) proof of feasibility by production of demonstrators/prototypes. It is likely that such R&D is best supported by a range of EU Instruments including STREP, NoE and IP. The industrial and academic communities working in storage and related areas are well aware of the need for strong collaborative actions to ensure the EU can take best advantage of these opportunities. A strong desire and willingness to co-operate has been engendered during the IMST series of storage workshops, and this is ripe for exploitation.

Figure 4.28: Possible EU research and development opportunities in the area of probe storage

System architecture and integration

development of probe array memories compatible with conventional IC processing
development of alternatives to traditional cantilever architectures
multiplexing, interconnections, coding, signal processing issues
cost reductions (simple architectures, fewest contacts per tip, passive rather than active actuation,

Media development

write-once or rewritable media or both?
phase-change, magnetic, polymer, other?
low power write (and read) operation
high density capability (sub 10nm bits)
cyclability and archivability

Nanoscale science

thermal and electrical properties on the nanoscale (ballistic conduction, quantum effects)
material processes on the nanoscale
netic switching.

Novel application areas

cache memories
raid architectures

5 Preservation of Cultural Heritage

One key issue, often neglected when considering electronic-based mass storage, is the question of the long term conservation of stored data. It has been often pointed out that we can still read books which are hundred, or even thousand of years old, and old photographic plates are still printable, but we do not know if electronically saved data will be still readable in a ten years time.

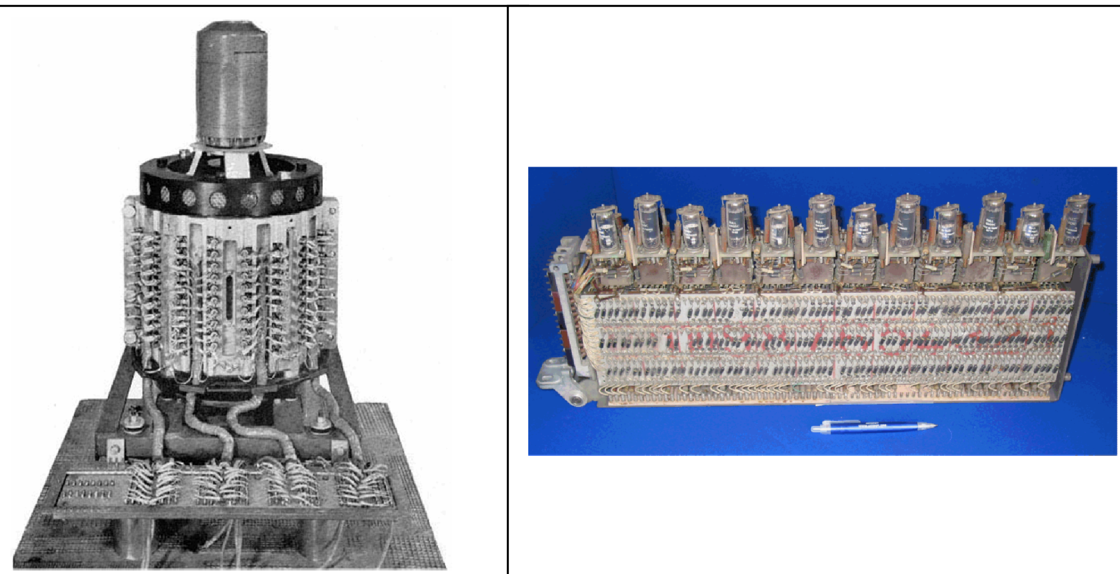
This issue is becoming increasingly critical, since there is a general move towards digitalization of texts and images, and towards the so called paper-less office. Moreover, an increasing part of music, images and movies is available only in electronic format. In order to avoid becoming a society with no memory of the past, a concerted action is needed to assure the conservation of digitally stored materials. The issue was raised even recently by Dutch Minister for Education, Culture and Science, Maria van der Hoeven, who suggested that the concept be awarded more importance at European level and introduced as a priority in the Seventh Framework Programme (FP7) for research.

The challenge must be met on two fields:

Storage standards: several standards are used to store data, some of them related to specific programs used to generate the file (e.g. PowerPoint, Freelance Graphics, Words, Acrobat), others more general (e.g. ASCII, JPEG, TIFF). These formats evolve quite rapidly (one generation every two-three years), and even if compatibility with previous generation is usually rather good, incomplete information recovery can often happen with older versions, and cross-portability is not always guaranteed. Again, more general standards have in general a longer lifetime.

Since most of these standards result from commercial products, it is probably hopeless to try to control them; anyhow an effort must be done to guarantee continuity. The solution could be in the form of an Association or Network, like a “European Bureau of Formats”, that insure the conservation of all main reading tools, hardware and software, and, if needed, takes care of developing, or having developed, conversion programs for formats or media which are in danger of losing information. A good example is the Dutch "e-depot" initiative, a cooperation between the Dutch National Library and IBM. It takes the form of a storage and retrieval system that automatically adapts to new technological developments. It automatically updates itself when computer programs, hardware and software are replaced.

Storage media: several electronic mass-storage media are in use, and are discussed in this document. The long-term life of the support and of the stored information is still matter of debate: in spite of all *accelerated* life tests, there is no guarantee that *all* possible failure mechanisms are covered. The real proof will be given only by long-term storage tests. On the other side, the fact that books and other traditional information storage media are so long-lived is related to their very high built-in redundancy: scratches, loss of a few letters, even loss of full pages do not, in general, significantly reduce the information content. The situation is completely different for electronic storage: the most commonly used formats are using compression to save memory space, and therefore the content is made even more sensitive to single bit failures. A possible alternative is to develop new information coding algorithms that maximize redundancy, taking profit of the continuous increase in memory availability. Special care should be given to the protection of the control characters, where a single failure could make all the text unreadable. The development of proper codes and algorithms should be subject of a dedicated research effort at European level.



Old technologies for memories: drum and vacuum tubes.

6 Recommendations to strengthen the European position

6.1 Rationale for a specific action on mass data storage technologies

Mass data storage now covers diverse technological areas, which used to belong to different academic and research communities and were often developed by different companies. To a large extent, this separation is no longer true, and more important, has to be ended. Indeed, many technologies are now competing on the same markets[1], and the frontiers are now evolving as new devices merge the know how of two communities and industries:

- Magnetic Random Access Memories (MRAM) are merging the fields of magnetic storage, for the materials, and of solid state electronics;
- Phase Change Memories (PCRAM) are merging the material know-how of optical storage, with system and process approach of solid state memories;
- Probe Storage is merging know-how from the field of micro-machining and microelectronics, for the system, with the one coming from magnetic or optical storage for the storing mechanism.
- …

Also, it is likely that building the intelligent memories of the future will require the combination of many technologies to fulfil the user's needs (huge capacity, fast access, easy retrieval of information…). In addition, some issues are common to all memory types and would benefit from synergies and adaptation of well consolidated approaches: Error Correction Codes and procedures, and in general, data handling techniques.

[1] For instance, optical / magnetic / solid state data storage for camcorders.

It is now needed to target the available research effort on the most promising and productive areas, and to ensure that the rich opportunities opened at the frontier of the existing technologies will be explored. The European research on mass data storage technologies benefited from a significant effort over the 5th and 6th PCRD (see the list of EU projects at the end of the Book). This effort strongly contributed to maintain excellence and cooperation at the European scale. Now, **the context is ripe for the creation of a specific action, gathering the efforts on mass data storage technologies, and benefiting from a specific budget**.

6.2 On international cooperation and competition, on formation

In many areas, there are intensive contacts, sometimes in alliances but also in competition, with academic and industrial groups outside Europe. These were and are still with the USA and the Japan, and the contacts with Taiwanese, Chinese (and more generally South Asia) groups are likely to be more important in the coming years.
It may be that, in some particular area, critical development for the EU research and industry would benefit from the addition of key competencies found in and out of Europe. It is of primarily importance to be able to join such international cooperations in a position of strength. **The development of suitable tools to support and handle such research programmes involving non EU based partners would be highly beneficial**.

Mass Data Storage technologies have always been generic technologies, as the need to push further the limits of integration and data density led to significant advances that next benefited to other technological areas. Still now, **the research on Mass Data Storage is a highly innovative and multidisciplinary one, and provides an excellent playground for the formation of technicians, engineers and researchers. EU priorities such as the Marie Curie actions could then find here real opportunities to develop high impact programmes**.

6.3 Specific recommendations

Mass data storage technologies enjoy a progress rate rarely met in other technological areas. Thus, **even in the short term (~ 5 years), real innovations and breakthrough are often required to fulfil the roadmaps**. At the European level, **the research effort should then support both the mid-term - nevertheless highly innovative - research required to stay in the race, and the long term research (> 10 years) that will create the disruptive opportunities of tomorrow**.

From an analysis of the roadmaps and of the opportunities opened by the current developments on Mass Data Storage, detailed recommendations are provided in each of the four technical chapters (Part 4), identifying the areas where a research at the EU level would be the most effective. Also, the best tools to be used (STREP, IP, NoE…) to develop a specific technology or area are suggested. Here below, there is a synthetic overview of the technical recommendations.

On solid state memories:

The EU enjoy a strong an active research and industry, with major players, in this area.

Along the evolutionary path (the evolution of the floating-gate architecture will still dominate the coming decade), due to the very fast evolution of the technology, innovations are required on both materials and concepts:

- Development and integration of new materials inside the floating gate cell and the storage node (such as new high-k materials, new conductive materials, nanocrystals…).
- Process integration for Non Volatile memories (new cell geometries…)
- New design approaches that are required to mask single-bit failures, and to define proper storage algorithms and architectures.

Along the disruptive technology path: new approaches need to be investigated for the technology nodes beyond 45nm.

- Radically new storage mechanisms (based on resistivity changes in molecules or other materials, on polarization or magnetic… effects), offers promising alternatives and are worth investigating now, taking into account the 10-15 years needed to go from lab scale proof of concept to industrial production.
- An active research on new architectures (3D…) is also required.

Optical memories:

Europe is playing an important role in optical data storage, with both a strong supply industry and high level research groups. Up to now, optical memories rely on removable media, coming on the market generation by generation (CD, DVD…). It is now needed to prepare the outcome of next generations of optical media by supporting innovation on

- Light sources R&D for deep UV laser diodes
- Near field recording: new materials, new optics, micro actuators MEMs based (heterogeneous technologies)
- 3D optical storage: new materials, new integrated systems, multilevel, holography; fluorescent technologies
- System: data rate, multiplexing, new concepts for signal processing, new systems (cards or others)

Magnetic Memories

The research on magnetic memories is at the highest international level in the EU, and, even where the European Industry is not the strongest, the major breakthroughs that are now required will open new opportunities do develop an economic activity from Start Ups, and to secure Intellectual Property in areas that will deeply impact the future of the advanced economies. Where the EU based industry is strongly active (MRAM…), a collaborative research will ensure the success of the current developments. Worth supporting are:

- The disruptive technologies paving the future of the Hard Disk: patterned and self organised media, new recording schemes…
- The emerging areas of magnetic storage, primarily Magnetic Random Access Memories *(Research power and production potential are both here in Europe, creating a major opportunity),* but also specific innovative developments out of the mainstream, such as magnetic logic.

Emerging technologies for Memories

A EU effort would be the most beneficial on the development of scanning probe-based memories. This is certainly the most advanced alternative to the established technologies, and Europe will here benefit from a top level academic research (around probe storage) and of the needed industry. Key areas to investigate now are:

- Materials able to meet the probe storage requirements (density, writing and reading speeds, cyclability…)
- Systems (MEMS for actuation, fabrication of tip arrays…)
- Novel application areas derived from probe storage (cache memories, MEMS-based array memories, ...)

In addition, wilder dreams, such as bio-inspired memories should be supported when offering an opportunity for breakthroughs.

Coordination:

Finally, there is certainly a deep **need for assessment and coordination activities on mass data storage technologies** to:

- support further the creation of a EU wide research community on mass data storage, cutting across the old frontiers between the different technical fields, and closely associating academic and industrial researchers
- provide the needed synthetic view of the competing technologies, taking into account the research breakthroughs, the market trends, the expectations of the consumers and developing a vision of the benefit for the whole society

7 Appendix: Main European Projects on Mass Data Storage Technologies

Solid State Memories:

IST projects:

RESPONSE (concluded): Study of the Stress-Induced Leakage Current in Non Volatile Memories, and tunnel/interpoly dielectrics improvement techniques. Its conclusions points out the need to investigate new Non Volatile Memory approaches, as in ADAMANT.

NOSCE MEMORIAS: (starting): investigation of new approaches to Non Volatile Memories, based on organic polymers and inorganic ferroelectric memory devices.

ADAMANT (in progress): feasibility demonstration of large industrial memory arrays, based on (Si, SiN) nanodots (made by pure LPCVD industrial techniques)

FRACTURE (in progress): fault-tolerant architecture for molecular nano-technology based non volatile memories.

FLEUR (in progress): development of embedded NVM (Non Volatile Memory) devices based on ferroelectric materials and their integration in a single chip with CMOS logic for SMART Cards / RF ID applications.

PC-RAM: (in progress): validation of the potentiality of a non volatile memory concept based on the phase transition of chalcogenide materials.

FECLAM (concluded): proof of an equipment concept suitable of producing ferroelectric layers based on chemical vapour deposition.

NANOMEM (concluded): to develop two new varieties of Tunnelling-MRAM (Magnetic Random Access Memory) based on two terminal device MIMRAM (Metal- Insulator-Metal RAM) and three terminal device TTRAM (Tunnelling Transistor RAM).

INNOVATION projects

IEDEA (in progress) transfer and validate a CMOS compatible Non Volatile Memory technology into an industrial manufacturing environment.

INTAS projects

Optically and electrically controlled Flash memory device based on self-organized quantum dot structures (concluded): development of a new type of nonvolatile Flash memory device based on self-organized quantum dots (QDs) as optically- and electrically-controlled traps for charge carriers.

ESPRIT projects:

PANORAMA (concluded): Definition of a new concept of NVM cell, storing charge in the spacers. The accent was on embedded applications, and easy compatibility with standard CMOS.

FELMAS (concluded): demonstration of the feasibility of high-quality PZT films of sufficient quality for non-volatile memory devices and their integration with existing CMOS technologies.

NEW MUSIC (concluded): explorative research on multi-level storage for NV memory applications.

APBB (concluded): integration of new-generation reprogrammable, read-only memory devices (both EPROM and EEPROM) for the application-specific IC (ASIC) market.

HIDICCA (concluded): development of a new generation of smart cards, which will combine high density non volatile memory technology with state of the art computer architectures and advanced security features, based on public key algorithms.

SPIDER (concluded): to assess magneto-electronic circuit applications in the fields of non-volatile memory, programmable logic and reconfigurable circuits.

NEW EMPHASIS (concluded): development of an application specific memory integrating flash and EEPROM functions on the same chip for use in cellular phone applications.

FET projects:

SASEM (in progress): fabrication of low-temperature single electron memories using SOI technology.

NANOTCAD (in progress): development of software package for simulation and design of a wide spectrum of devices (including single-electron transistors and memories, resonant tunneling devices, quantum dot devices).

FASEM (concluded): techniques for the high-resolution nanofabrication of coupled islands for single-electron devices

GROWTH projects:

NEON (in progress): Investigation of advanced ion-implantation and molecular beam epitaxy techniques for the formation of well defined (Si, Ge) nanocrystals and demonstration in memory cells.

EUREKA projects

JESSI

T22 **“Embedded memories”** (concluded): development of embedded memories, including also Non Volatile Memories.

MEDEA

T502 **“Options for 0.35 µm CMOS”** (concluded): included activity on embedded FG NVMs.

T509 (concluded): Technology for Embedded and Application specific High Density Flash Memory.

T552 **“MUSIC”** (concluded): included activity on embedded NVM for 0.35 and 0.18 µm technologies.

MEDEA+

A302 **“Esp@ss-is”:** development of an advanced smart-card system, including dedicated Flash memory architecture.

T123 **“CRESCENDO”** (started 2001): includes activity on embedded NVM for 0.18 and 0.13 µm technologies. As for the previous projects, the accent is on the use of a consolidated approach (Floating Gate) to minimize risks. **ADAMANT** aims at introducing a new architecture for NVM, which could be integrated in products, beyond the 0.1µm node.

T126 **“BLUEBERRIES”:** mainly on design and system architectures for embedded memories, includes also exploratory activity on embedded MRAM.

2T201 **“NEMESYS”** (started 2005): targets embedded NVM for 90 and 65 nm, including exploratory activities, in cooperation with research centres, on innovative technologies like nanocrystal-based floating gates and high-k dielectrics.

Optical Memories

BLUESPOT (concluded): Technology for optical recording with blue lasers, mainly devoted to disc technology.

SLAM (concluded): Investigation of near-field and multiplexing technologies for ultra-high density optical recording.

FAMOUS (concluded): Ultra flat plastic discs and sliders for high-density magneto-optical recording.

MAMMOSIL (concluded): high-density magneto-optical recording, mainly media.

TwoDOS (concluded): Two-dimensional coding and experimental tests of this to achieve a 10-fold increase in data-rate and double capacity.

ATHOS and **MICROHOLAS** (both in progress): Holographic data-storage for high capacity optical recording.

Magnetic Memories

TUNNELSENSE / BRITE EURAM BRPR-CT98-0657

Wafer scale high performance magnetic sensors based on spin dependent tunneling

(1998-2002)

MASSDOTS / Esprit n°32464

Magnetic switching in submicron dots (Massdots)/

(1999-2002)

NANOMEM / IST CT-1999-13471 (FP5)

Semiconductor free nanoscale non-volatile electronics and memories based on magnetic tunnel junctions

(2000-2002)

AMORE / GROWTH G5RD-CT-2000-00138 (FP5)

Advanced magnetic oxides for responsive engineering

(2000-2003)

NANOPTT / GROWTH G5RD-CT-2000-00135 (FP5)

Conductive Nanowires For Applications In Microwave, Magnetic And Chemical Sensing Devices Based On Polymer Track Etched Templates

01/02/2000 - 20/02/2003

MAGNOISE / IST-1999-10849 (FP5)

Noise in magneto-electronic sensors

01/01/2000 - 31/12/2002

MAMMOSIL / IST-CT-2000-28278 (FP5)

Development of the MAMMOS technology for magnetic recording

(Nov. 2001-Oct. 2004)

SPINOSA / IST-2001-33334 (FP5)

Spin polarized injection in nanostructures and devices

01/01/2002 – 12/31/2004

NEXT / IST-2001-37334 (FP5)

Nest generation of MRAMs with thermally assisted switching

01/09/2002 - 30/08/2005

MAGLOG / FP6-510993 (FP6)

Exploration of magnetic logic

17/05/2004 - 16/05/2007

BLUEBERRY / MEDEA^{+}

MRAM development for embedded memories

2003-2005

Emerging Technologies

FET projects

InProM : Integrated Probe Memories (2002-2003) – The project ended with the demonstration of Tbit.in^{-2} electrical probe recording in a phase change media. The proposed approach has a high competitivity with respect to other on the energy consumption, it remains to assess the eras ability of the stored information.

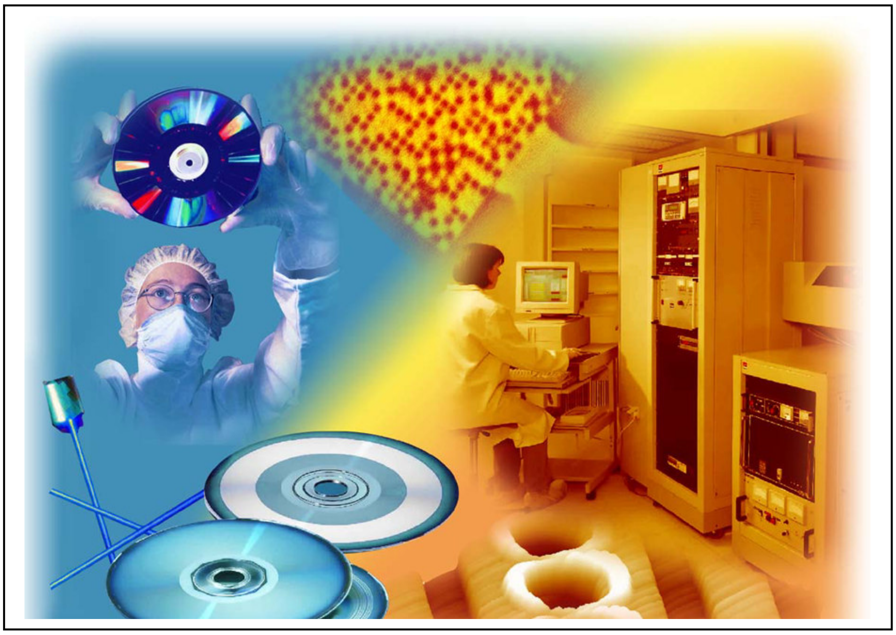


Image taken from the IMST Conference graphic file