INNOVATIVE MASS STORAGE TECHNOLOGIES

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INNOVATIVE MASS STORAGE TECHNOLOGIES
"IMST White Book"

MEMORIES
For future Electronic Systems
A road map for the
European R&D

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Solid state memories

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Magnetic memories

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Emerging technologies

And the collaboration of Thomas REIBE (EC/Brussels)

INTRODUCTION

Memories: always a strategic component…..

By itself, a memory is always a strategic part within an integrated component. In addition, 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 is due to the fact that, as the race towards higher capacities and performances never stopped, Mass Memories implied both the continual improvement of existing technologies, but also the development of radically new approaches to overcome the limiting barriers associated with a given technology. Fig. 1 illustrates this continuous introduction of radically new technologies.

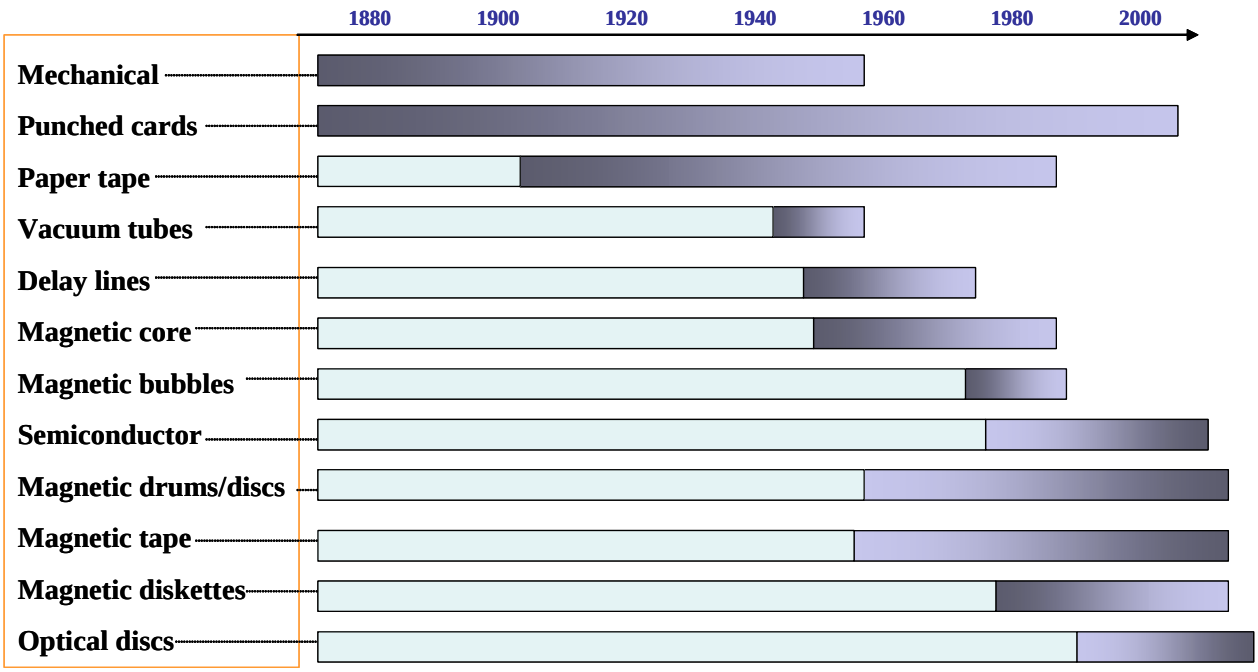


Fig.1: Life time and evolution of the memories technologies

This race implied the use and improvement of diverse and wide parts of the available technological know-how, to the point that the main modern technologies have been applied to elaborate new, high density, and fast memories:

- Mechanics
- Electronics and semiconductors
- Magnetic
- Optics

The progress obtained in these generic technologies led to breakthroughs such as miniaturized actuators (drives), computers, hard disk and actuators, optical memories and telecommunications. All these technologies are intensively used in different market segments such as health care, automotive, audio and video, in house use, robotics, security, banks, agriculture, food ….

Europe played an important role in both R&D and industrialization. Large European companies such as Philips, ST Microelectronics, Thomson, Infineon, Siemens… and implanted one such as ATMEL, IBM, SEAGATE, ALTIS have created a large amount of activities. Now, the prospect for job creation may be leaner if Europe cannot avoid the move of production facilities towards areas with lower labor costs but good and improving technological and scientific level (primarily Asia).

To keep these activities in Europe, the European R&D must be able to develop continuously new technologies. Indeed, it will be a very significant challenge to locate the mass production of mid and low technologies (/ high technologies) in Europe till the Asian countries have joined the European life level (and here, the time scale is largely unknown). To a large extent, the most effective paths are well known:

- Intellectual property : creation of patents and royalties exploitation
- Creation of very new concepts leading to technological ruptures and use in new companies such as “start up”
- Development and production of high technologies products in existing companies.

In every case the key of success is at the R&D level.

We must not forget the European strategic interests in key areas of knowledge such as

- Energy
- Mechanics
- Computing

that are essential for the industrial activity of tomorrow.

If we go deeper in these technologies we always encounter the need of memories, mass storage or logic.

The IMST conferences

The creation of the Innovative Mass Storage Technology workshop built up on these considerations. In addition, there was no pre-existing 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. However, it is each day clearer that these technologies are or will be competing on the same market: the most striking instance is the (magnetic) minidisk that competes with Flash memories for video camera recording.

As a result, the industry can't develop its activity at the moving frontier of knowledge in any of these fields without having a close look to other mass data storage technologies. In addition, magnetic and optical technologies 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.

Launched at the initiative of B. Bechevet, Y. Samson and V. Gehanno, IMST 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 will be organized in Aachen (Sept. 28,29) and will capitalize on this success and on the new appetite from the community for this specific event.

The elaboration of a "White book" for mass storage technologies road map is the logical 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 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.

In no way, the report can be seen as reflecting an official position from the companies or institutions of its authors.

1- Market activity:

The activity and budget of the mass storage memories are huge and show a constant growth over the past decade. Looking at the repartition of the technologies used *, more than 90 percent of the new information was stored on magnetic media, with just 7 percent stored on film and a fraction on paper or optical media (Siliconvalley.com Posted on Wed, Oct. 29, 2003).*

The information stored in 2002 is of the order of 5 'exabytes' (By Kristi Heim Mercury News Seattle Bureau).

Looking at the different charts that we can found in the market evaluation (here from IMMS web site) we can point out that in 2003 the revenues from HDD are behind the ones from the flash. The total of flash and HDD (5275) is very close from the total of the rest (Table 1 and table 2). Another figure of this activity is the constant evolution of the technologies. This is particularly true in the domain of the CD and DVD technologies as shown in the tables 3, 4, 5. Rewritable technologies have been cancelled by writable like CD-R and DVD-R. This evolution was very difficult to plan and the polymer technology not foreseen for this application. On an other side all the researches made on Magneto Optical discs (MO) have not given the industrial production forecasted and could not give the feedback revenue.

In conclusion of this very synthetic overview of the market activity, we have to notice that the revenue coming from the production of mass memories is very different from the volume of

production (number of memories or drives). This is particularly true between flash and HDD, on one hand the byte cost of HDD is roughly 10^3 lower than the flash byte, on the other hand the revenue is in the same order. This demonstrates also clearly that the benefit of this market is:

- On the starting production of new high technological solutions
- On the royalties and licenses.

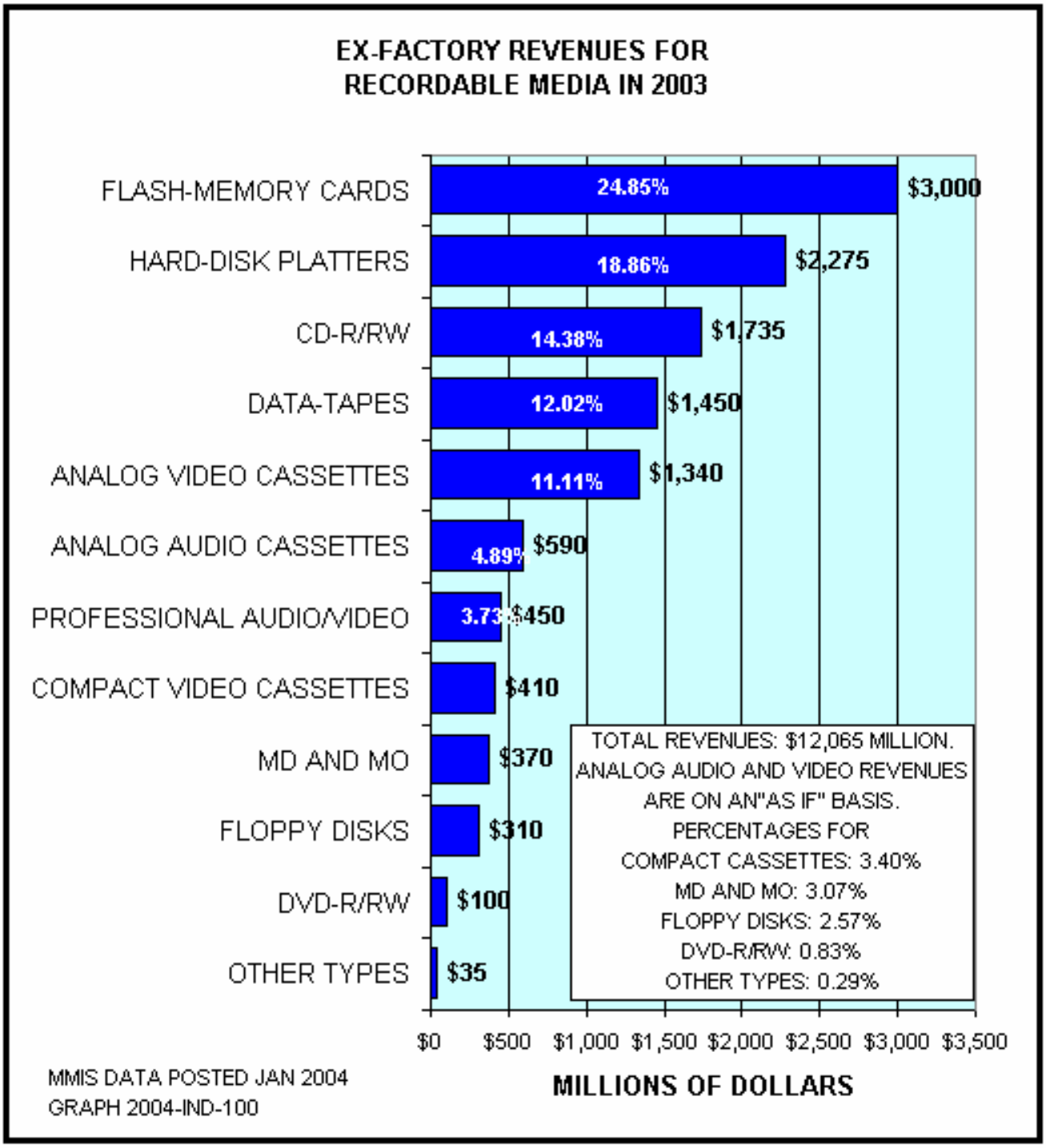


Table 1

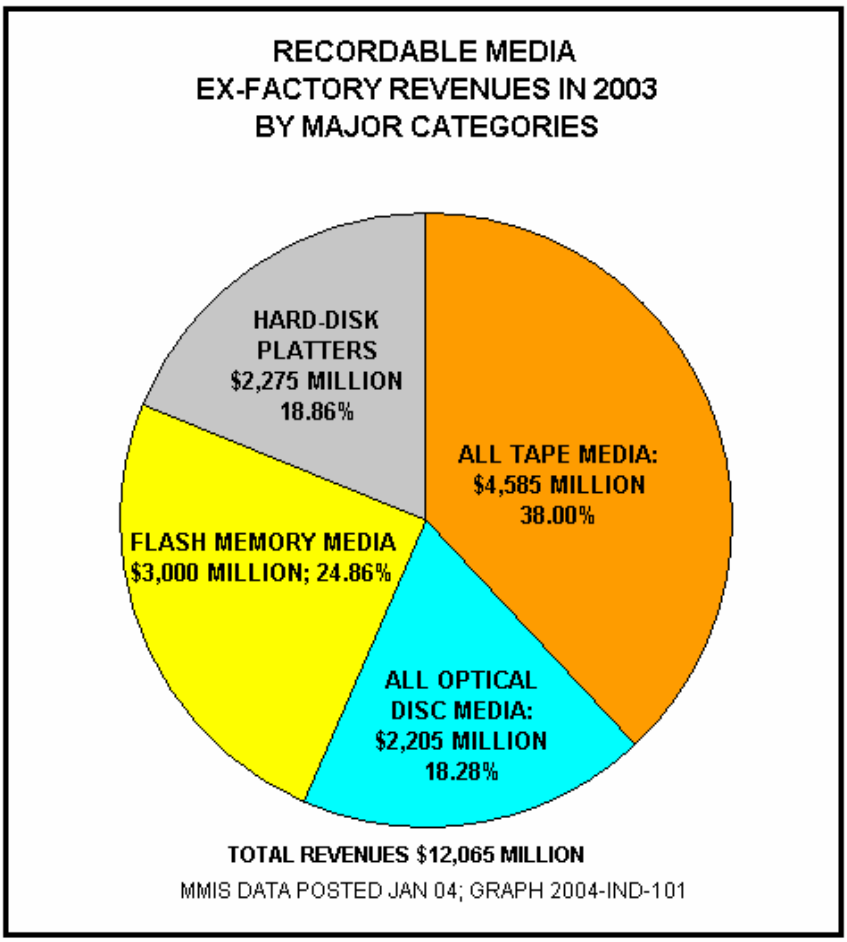
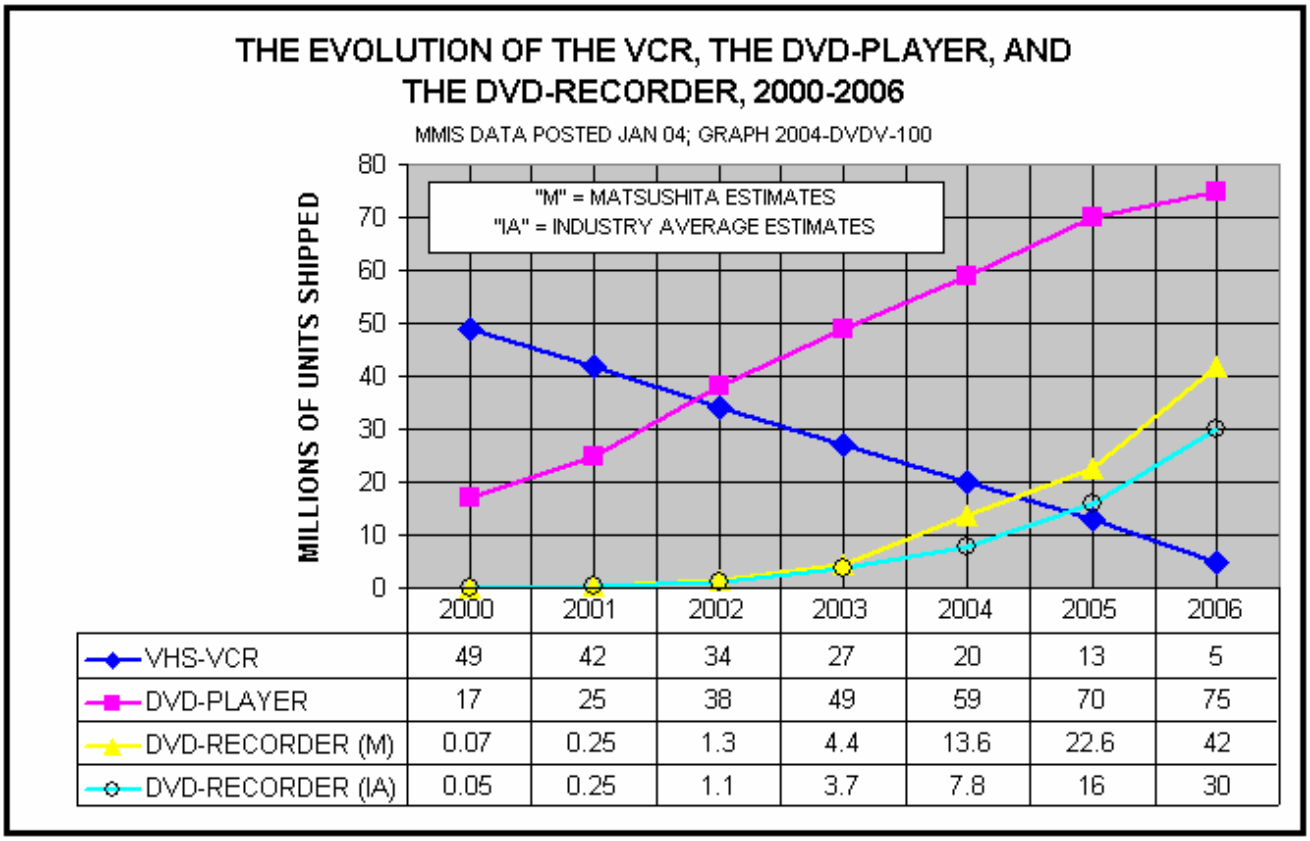


Table 2



	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

Table 3

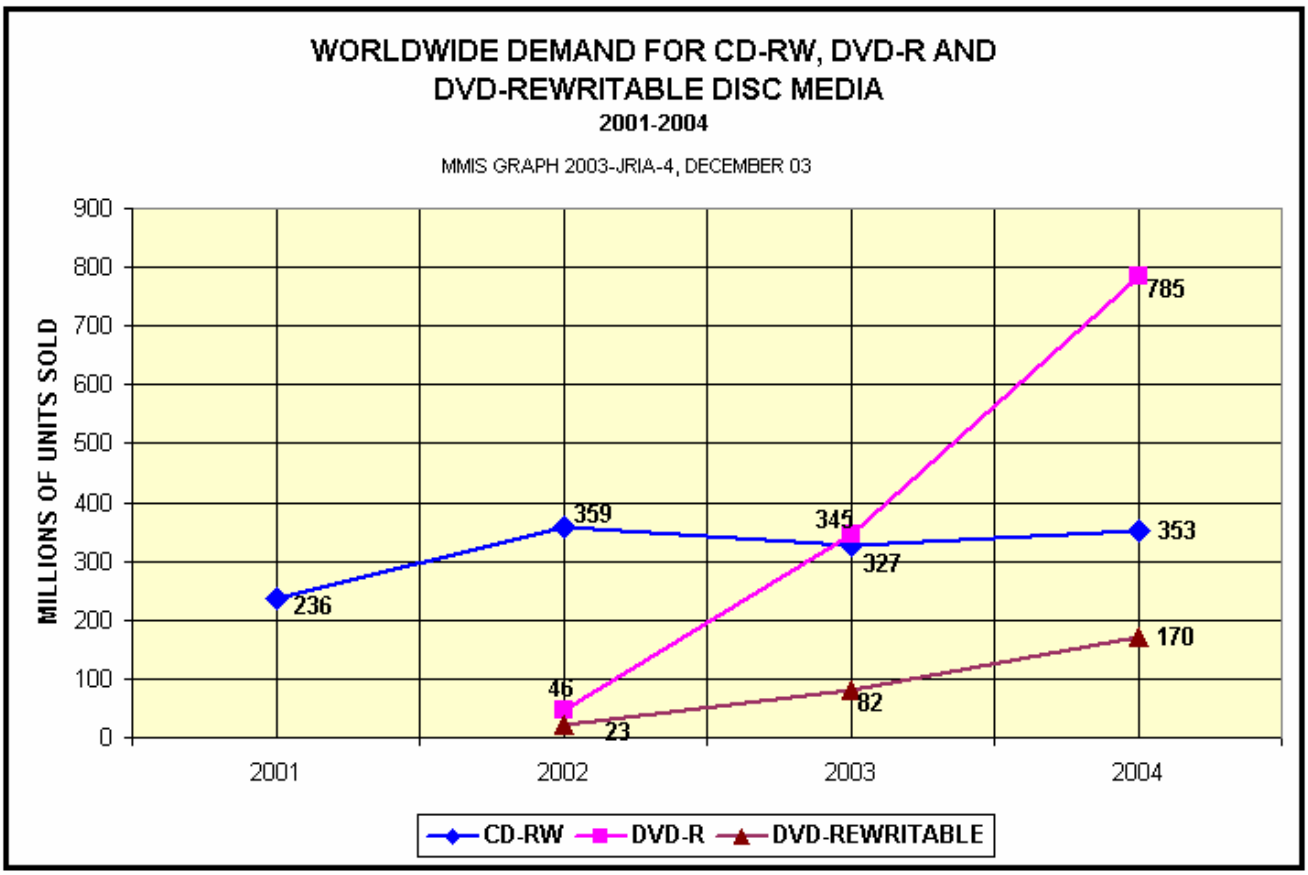
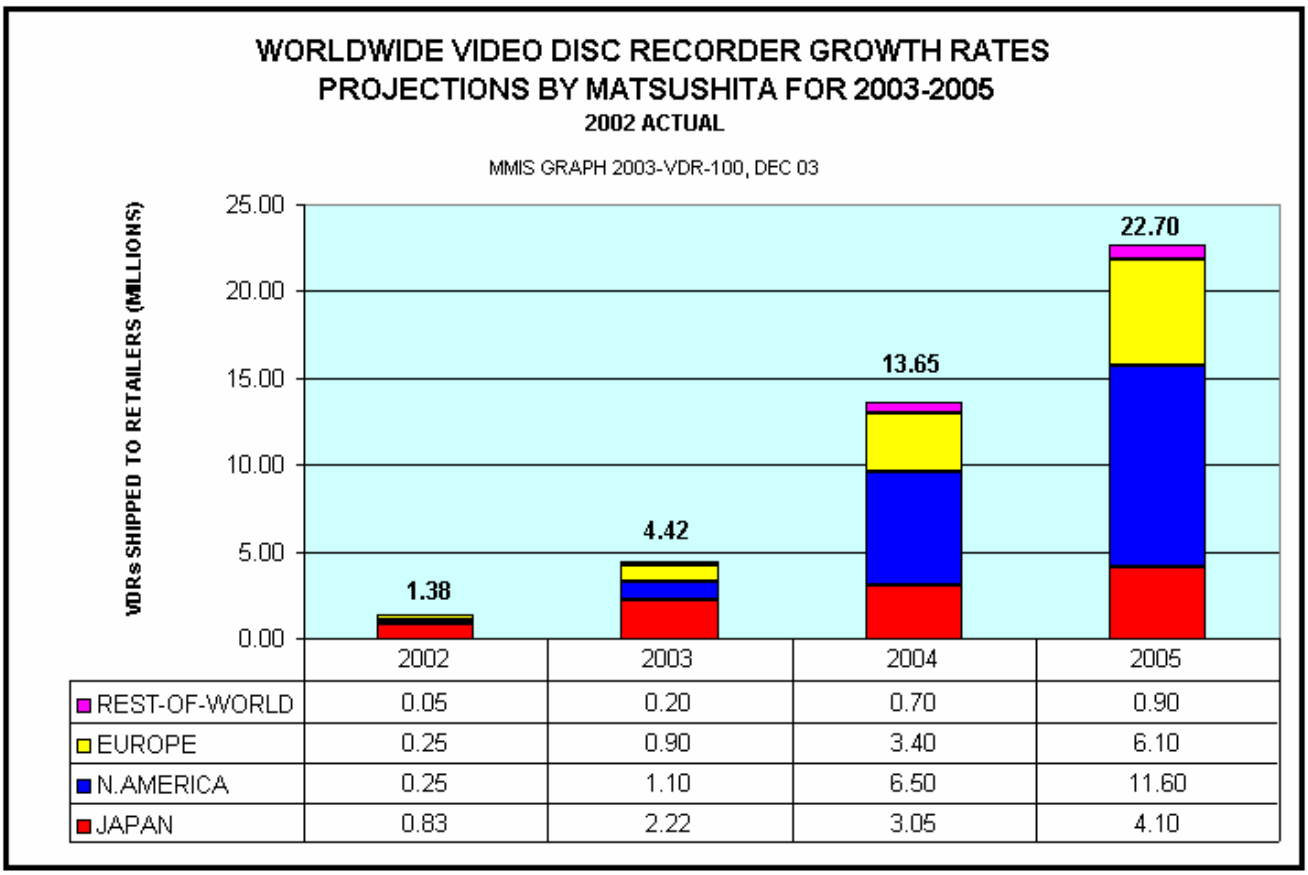


Table 4



	2002	2003	2004	2005
REST-OF-WORLD	0.05	0.20	0.70	0.90
EUROPE	0.25	0.90	3.40	6.10
N.AMERICA	0.25	1.10	6.50	11.60
JAPAN	0.83	2.22	3.05	4.10

Table 5

2. MAIN RESEARCH AREAS

2.1 SOLID STATE MEMORIES

2.1.1 Memory Technology

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.

2.1.1.1 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.

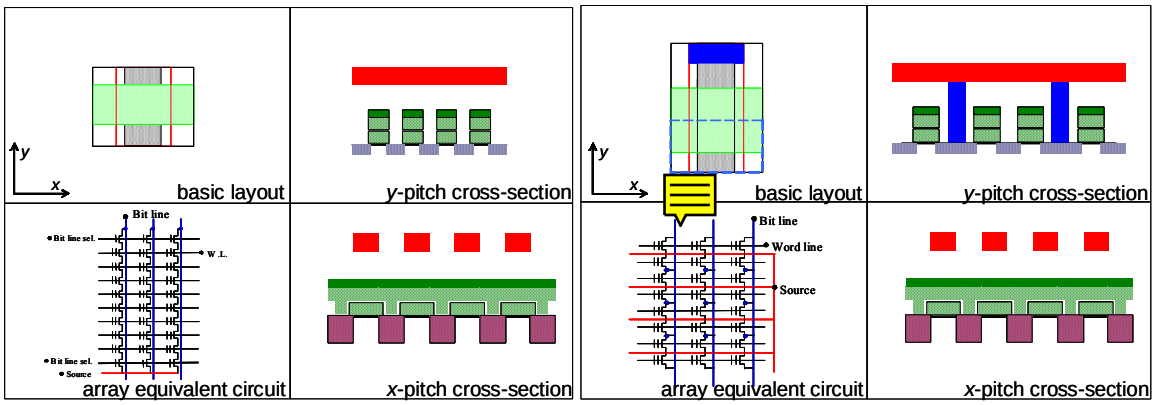


Fig.1: scheme of NAND and NOR memories

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 0.025μm^2 for NAND at 70nm technology node (Samsung, IEDM 03).

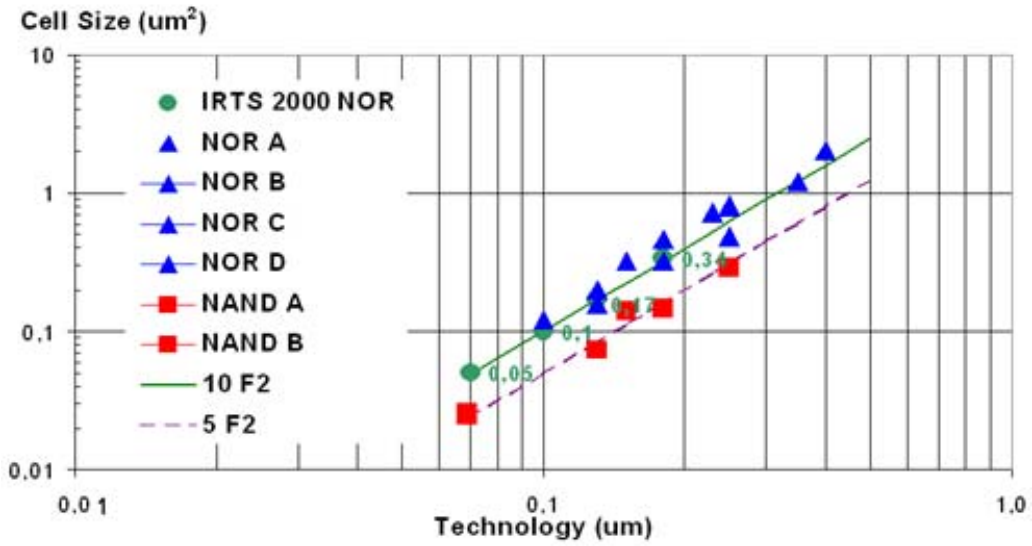


Fig.2: evolution of Flash memory cell size

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	2001	2004	2007	2010	2013
	Technology node (nm)	130	90	65	50	35
Flash NOR	Cell Size (λ^2)	10	10	11-14	12-15	13-16
	Cell Size (μm^2)	0.160	0.081	~0.053	~0.034	~0.018
Flash NAND	Cell Size (λ^2)	5,5	5,5	4,5	4,5	4,5
	Cell Size (μm^2)	0.093	0.045	0.019	0.011	0.006

Table 1: 2002 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
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 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.

2.1.2 Status of the Market

At the moment (2003) 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, probably already in 2004, 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.

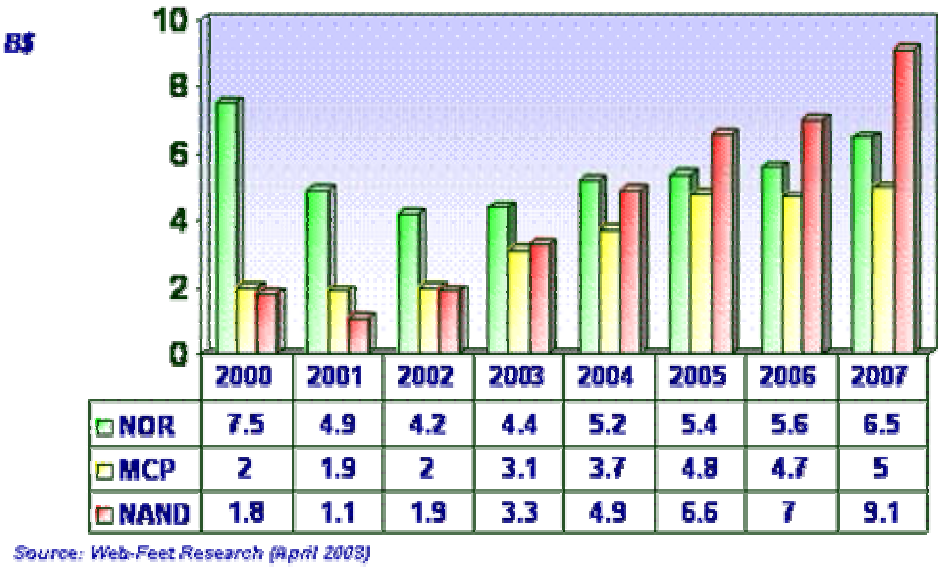


Fig. 3: NOR and NAND market trend.

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 (fig. 4).

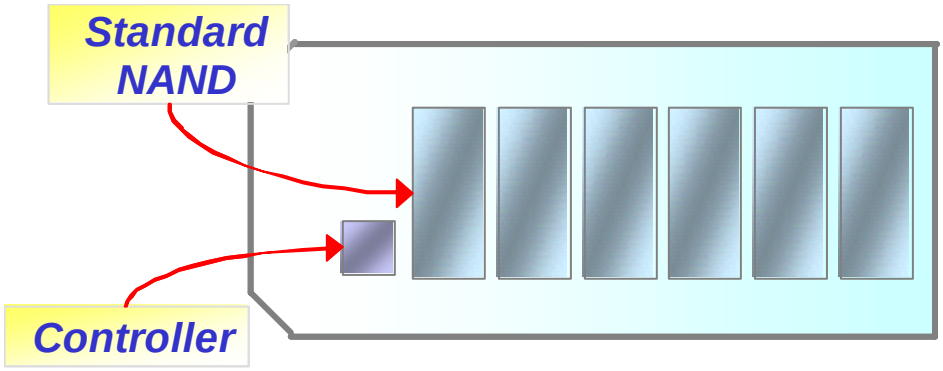


Fig. 4: schematic layout of a Flash card

Today different type of Flash cards is present in the market: Compact Flash, SmartMedia, Memory Stick, MultiMedia Card, Secure Digital, Picture Card (see fig.5).

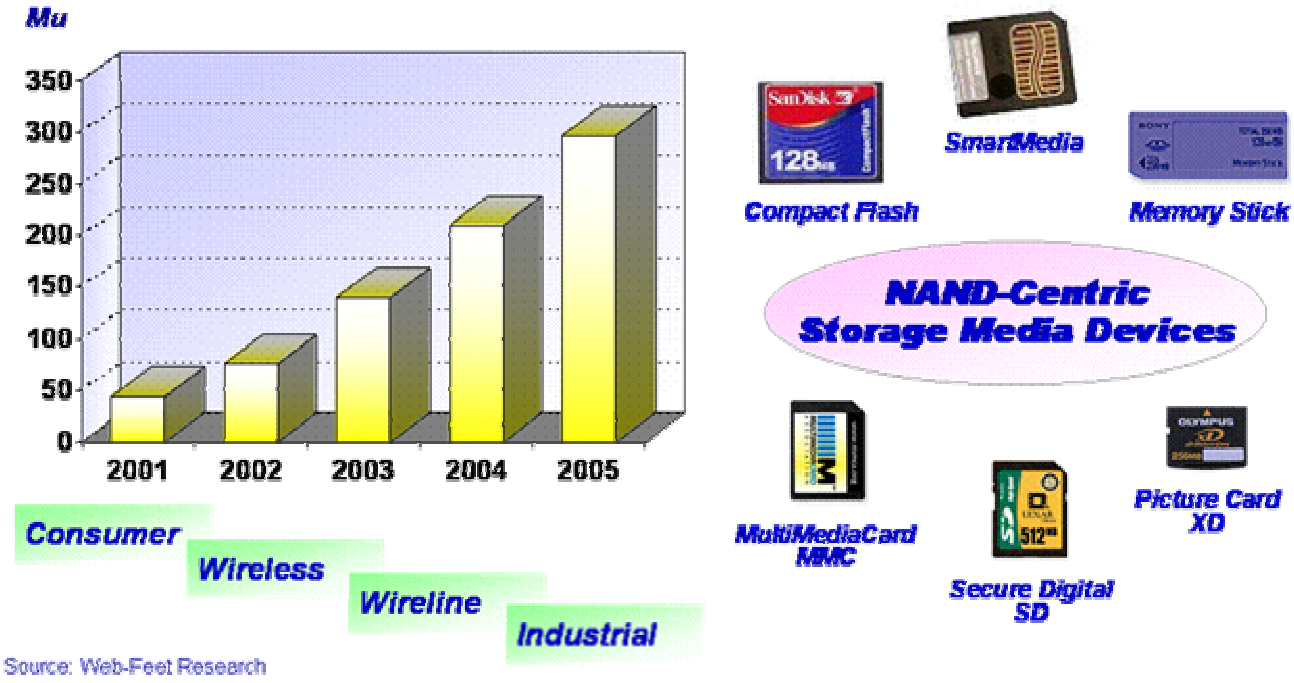


Fig.5: Flash cards formats

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.

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.

Main players in Flash memory field are reported in Table 3. There is still a dominant position of Intel, which holds a 27% share of all NOR Flash market, but in recent years Samsung and Toshiba have emerged as the key player in the field of NAND Flash, and are now grown to the second and third position overall, thanks to their position of supremacy in the NAND market.

2002 Rank	2001 Rank	Company	2002	2001	Pct Change	2002 Marketshare
1	1	Intel	2,127	2,110	1%	27%
2	9	Samsung	1,100	300	267%	14%
3	5	Toshiba	858	585	47%	11%
4	2	AMD	795	1,133	-30%	10%
5	3	Fujitsu	670	865	-23%	9%
6	4	STMicroelectronics	609	682	-11%	8%
7	7	Mitsubishi	405	450	-10%	5%
8	6	Sharp	395	455	-13%	5%
9	8	Atmel	360	340	6%	5%

Tab. 3: ranking of top 8 Flash memory manufacturers (source: IC Insights)

The main players in the area of Flash Cards are Toshiba (in association with Sandisc), Samsung and Renesas.

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.

2.1.3 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.
- 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. Philips has cooperation with Motorola and STMicroelectronics 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).

2.1.4 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 Appendix 1.

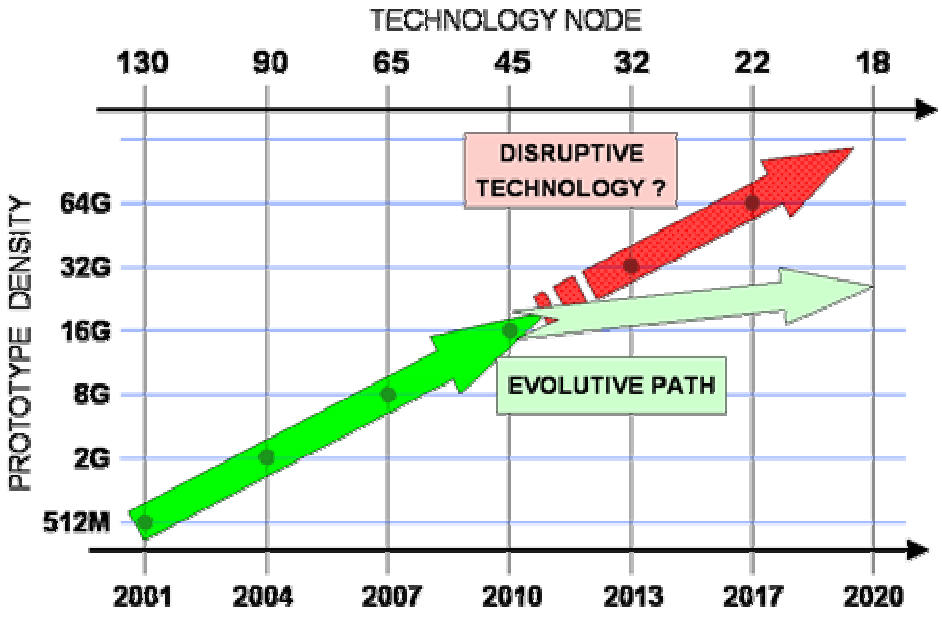
To support European industry through the foreseen explosive growth of mass-storage applications, extensive research activities are required that could focus the know-how, which already now exists in different European Universities, Research Centers and Industries. Integration of different disciplines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



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:

- Basic investigation of new storage mechanisms: 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;
- Investigation of integration properties 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.
- The final proof of feasibility 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.

2.2 OPTICAL DATA STORAGE

2.2.1 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 replicated optical discs was over 11 billion units, and to that impressive number 6 billion recordable discs could be added. This multibillion discs business 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 storage product for the consumer electronics market. It became the media of choice for digital audio, and later also for software 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 penetration of DVD into the homes of the consumers is spectacular and unprecedented.

The number of optical discs drives for PCs shipped in 2003 is about 200 million. In the audio-visual domain, DVD players are taking over the lead in the market place of the VHS-tape recording systems. This has already happened for playback of pre-recorded material, and 2004 will be the first year in which the number of units sold for video DVD-recorders will exceed the number of VHS tape recorders.

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

- An optical disc has become a low-cost publishing medium for the content industry,
- Increments of the capacity of collection 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 exchange between users, also as a tangible gift
- Content can be removed from the reader for security / privacy and for archiving
- Customer can make their own discs, with a writable system.

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). 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 capacities and higher data rates.

Several companies, including Philips and Thomson, have already 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. These Blu-ray Disc products are already on the market in small numbers. They are expected to sell in high volume in 2005. 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.

2.2.2 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 in today's market 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 discs.

Each of these formats provides a complete family of read-only discs (ROM), rewritable discs (DVD+RW, BD-RE) and recordable (R) or write-once discs. The ROM discs have triggered research an development on laser cutting (or mastering technologies). The rewritable discs have triggered a significant amount of materials research on the doped-alloys of 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 or to generate new options.

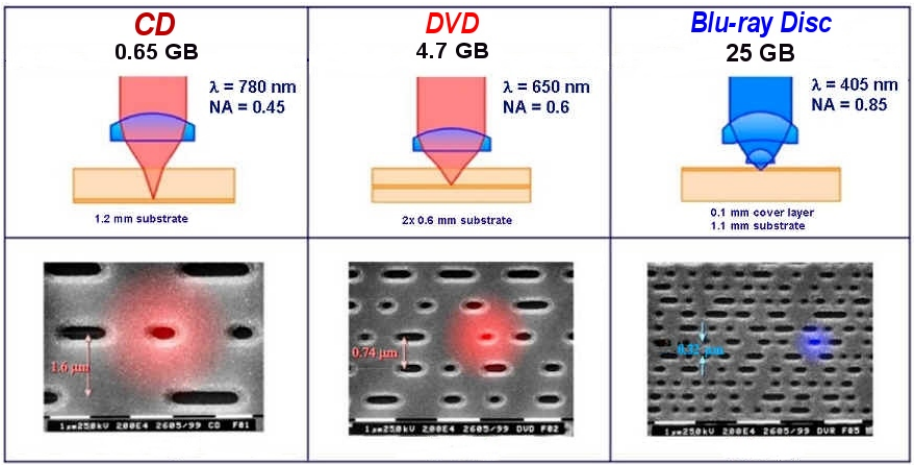


Fig.7: Three generations of optical discs. With decreasing wavelength and increasing NA

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.

2.2.3 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 stage 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, and this is now mass manufactured product. For DVD, the improvement of the system is going into mass-market products now. The speed improvements for new DVD recorders are expected to be completed in one or two years from now. For Blu-ray Disc, we are only at the beginning: First products are coming out now, and still a lot of problems are to be solved 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 is clearly entering 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 are 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.

2.2.4 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.

2.2.4.1 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 a recent IST project. By arranging pits on a hexagonal 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, and with 10 times the speed. So far this has been realized for read-only pits. Further experiments are to be done on recordable systems.

Fig. 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 30 GB.

2.2.4.2 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 directed to acquire a fundamental understanding of the relevant structure – property relationships in phase change materials.

Fig.9. A semi-transparent phase-change disc for multi-layer optical recording.

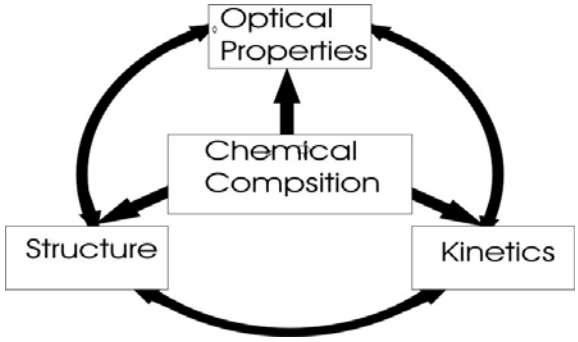


Fig. 10: Schematic diagram by M. Wuttig for the interplay between structural, dynamical and optical properties of phase change materials.

2.2.4.3 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 recent experimental evidence, both from Philips and from Sony, that the situation could be more favourable, and we could cross this barrier in future commercial product.

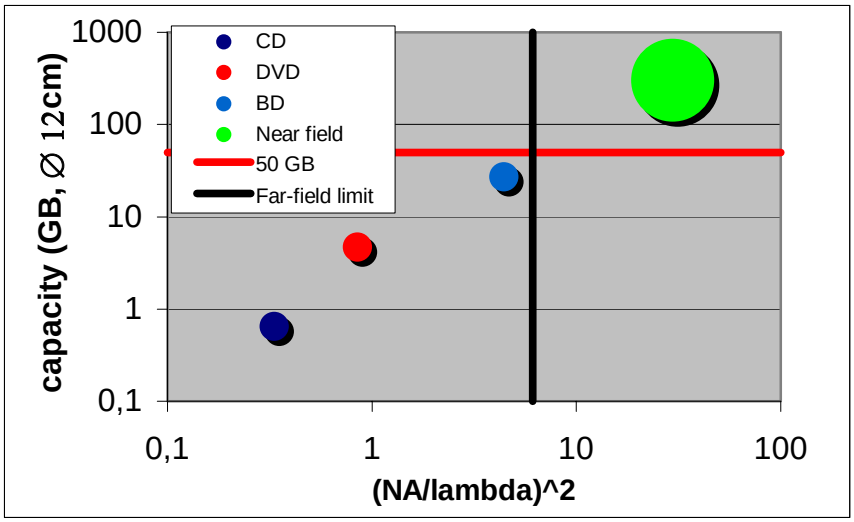


Fig. 11: The brick wall of optical recording. For a wavelength of about 400 nm and a Numerical Aperture (NA) of about 1, we leave a regime that has been exploited by CD, DVD and BD, and enter a new regime with new physical challenges.

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). This could be topics for exploratory research projects.

Fig. 12: A replicated lens for deep UV phase change recording by Philips Research.

An NA above 1 leads to higher achievable densities. But it also creates problems, both conceptually and in practical construction of the system.

The conceptual problem is that for these lenses, evanescent optical waves become important. These evanescent waves die out when they are made to escape the lens. They are able to probe features on a disc only when then disc and the lens are very closely together. However, when the disc can come that close, a rich variety in optical effects can be used to probe sub-wavelength features in the disc. The near-field optics has been a research topic in the IST project SLAM. But 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 this that the lens should be able to approach the disc up to distances of well below 50 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. Prof. Jenkins from the University of Plymouth proposes to study the behaviour and control of sliders at even lower flying heights.

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.

2.2.4.4 Optical multiplexing

Prof. Braat from the Technical University of Delft proposes to use multiplexing techniques to increase the storage capacity. The idea is to store more bits of information in one location. Because of the higher number of bits that are stored in one optical effect, the size of the effect itself does not need to be reduced to far submicron size. This means that the read-out of the high-density disc can be carried out at relatively modest values of the ratio λ / NA, 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. Two multiplexing methods may be studied: Optical data storage, using far-field illumination and detection, could be based on colour-encoding of the information, or it could use polarization encoding.

2.2.4.5 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. But 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.

2.2.4.6 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 could be started into optical card readers, or other systems, 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 and reduced power consumption. There is room for revolutionary ideas in this type of research, and for cross-fertilization with other fields of storage physics and technology. Prof. Jenkins of the University of Plymouth has proposed work on optical storage systems without moving parts, and also Philips has published on an optical card system at the 2003 IMST conference in Grenoble.

2.2.5 Situation in Europe

The optical storage industry is important for Europe, and Europe is important for the optical storage industry. Various companies have activities in optical storage: Philips makes optical drives and components around Eindhoven, and driver ICs in 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 (Liechtenstein) and Arburg and Singulus (Germany) are major manufacturer of optical disc production lines. Plasmon (Melbourn, UK) makes professional optical disc archiving systems for enterprises. Europe has a number of replicator companies like MPO (France), Sonopress (Germany), Sentinel (Belgium) and others. Bayer, Ciba Geigy and Clariant produce polymers and dyes for the optical storage industry. Toptica (Germany), Datarius and AudioDev (both Austria) make professional testers for optical discs.

Europe has a number of universities and research institutes that have significant contributions to the optical storage field. LETI in Grenoble has done important work on phase change materials for optical discs. Universities like Exeter, Hanover, Plymouth, Aachen, Delft, Dublin, Nijmegen, Cambridge, Imperial College London, Lancaster, Limerick, Brussels, Amsterdam, Ghent, Eindhoven, Manchester and others have been active in research in this field in previous European community funded projects. The optical storage field is highly interdisciplinary, and provides in excellent training opportunities for young scientists. Many of the significant developments in recent years have grown at the interfaces between disciplines.

In this field there have also been intensive contacts, sometimes in alliances but also in competition, with academic and industrial groups outside Europe. In particular the contacts with Taiwanese and Chinese groups are likely to become more important in the years to come. A collaborative and strong European effort in this area, will help EU based industry and academia to deal with these contacts from a position of strength.

2.3 MAGNETIC DATA STORAGE

The "School of Information Management and Systems" at University of Berkeley recently published a comprehensive survey on the flow and 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 §2.1 of this report still represent a very small total storage capacity). One trend shown in this survey directly interests this part: magnetic storage, already dominant in 2000, is still increasing its share in a market where the volume of new information increases at a rate of about 30% per year. And in year 2002 about 92% of the recorded newly created digital information was recorded on magnetic media. However this seemingly bright future does not benefit equally to all types of magnetic recording, and one must also to take into account the increase of device recording capacity observed far all techniques, which is sometimes much faster than 30% per year. We will detail that below.

But as a whole, 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 includes optical recording media).

The total magnetic storage market is expected to reach US$ 53.1 Billions in 2004. Essentially three technologies share this market:

- hard disk (HD) remains the best compromise in terms of cost/bit, speed and storage capacity, with new consumer applications rapidly expanding,

- tape storage keeps the lowest cost/bit and higher storage capacity, and cartridges are removable, which somehow makes it a 3D storage. So it remains heavily used for data archival.

- magneto-optical (MO) storage, usually more considered as optical storage, occupies a niche market for rewritable audio recording (minidisk).

In parallel a new magnetic storage technology is emerging, that of Magnetic Random Access Memory, evoked as a disruptive non volatile solid state memory technology in §2.1 of this report.

2.3.1 Mainstream technologies

2.3.1.1 Hard disk storage

Hard disks store the largest part of newly created information (circa 30 to 40% in 2002). In the mean time, hard disk technologies are the fastest growing segment of all storage media for information. The origin of this record breaking evolution stems directly in the progress of technology.

Technology and limitations

Areal recording density (in Gbit per square inch (psi) or GBit/in^2) is a useful criterion to evaluate hard disk technology. Figure 1 shows the evolution of areal density since the introduction of hard disk by IBM in 1957. This trend is by far less stable than for instance Moore's law for semiconductors, which actually shows that hard disk technology has been pushing its limits since its beginning. Each break in the curve corresponds to a technological breakthrough. The two most recent came in 1991 and 1996, when introduction of respectively magnetoresistive head and spin valve head drastically increased reading sensitivity and allowed to rise the growth rate up to more than 100% per year. This had remarkable effect on the hard disk market, as we shall discuss below. As seen on Fig. 1, it also put tremendous pressure on research as products are now less than two years behind laboratory demonstrations.

Here are some numerical examples of hard disk technology today:

- products are already at 70 Gbit/in^2, while the latest demo (end of 2002) was only at 110 Gbit/in^2.

- on the magnetic media, this last demo corresponds to bit length of 30 nm and track width of 194 nm, comprising about one hundred grains of diameter ~9 nm.

- disk rotation speed reached 10000 rpm. 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.

- and to keep spatial resolution and sensitivity the head flies at only 15nm above the media, to compare with contact separation evaluated at 10nm..

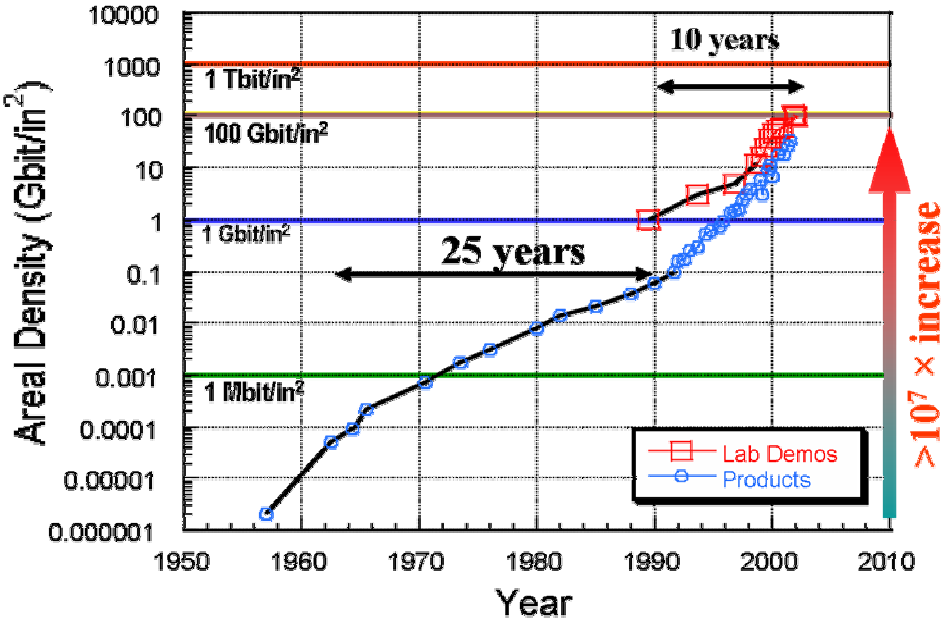


Figure 1

(© D. Weller,Seagate)

Expected 1 Tbit/in^2 density, to be reached probably before 2010, will represent bit length of about 10nm for track width 64 nm. This cannot be reached using today technology and certainly requires major breakthroughs.

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, C, etc. 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 increasing K and 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.

Current research objectives directly stem from this frustration:

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

- 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, furthermore including a soft magnetic underlayer of stringent properties. And the head design is also more elaborated. The shift from longitudinal to perpendicular is expected to happen around 100 to 200 GBit/in^2, and will allow reaching areal densities of 500 GBit/in^2, maybe more. Lab demos with perpendicular media already show slightly enhanced densities.

- 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 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 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 hard disk recording, where a laser pulse would heat 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, 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 could be reached using near field plasmon techniques.

- for micromagnetic and sensitivity reasons today's 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 and current perpendicular to plane configuration. Promising candidates use either giant magnetoresistance, or spin dependant tunnel magnetoresistance. However a major breakthrough would be to develop a non magnetic head.

- 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 rotation disk by a probe storage technology (cf §2.4 of this report). Magnetic probe storage will have to solve the writing problem anyway, but may bring lower energy consumption at operating.

- 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 Hitachi microdrive already tries to compete with Flash memory cards.

Status of the market

The hard disk market, already at 20.6 B$ in 2001, is expected to reach 50 B$ in 2006.

Figure 2 shows the evolution of the number of drives sold since 1995. To give an order of magnitude, about as many hard disk drives were sold as TV sets in year 2000. The low around 2001 corresponds to a depressed demand for small computers. The demand picked up in 2003, with 235 Million units sold, and 2003 also brought the opening of new consumer markets. This was made possible by the extremely fast increase in storage areal density observed in the last ten years, as shown in Fig. 1. Hard disks now give storage capacities above 100 Gbytes, with ever decreasing cost/Gbyte (less than 1 US$/Gbyte in 2003), or can be presented in very small form factor for portable applications (down to 1 inch for the microdrive, with 4 Gbyte capacity within the format of a Compact Flash memory). This capacity now allows taking advantage of the traditional bests of hard disk: much higher data rates than tape and even optical storage, quasi random access. New consumer applications are:

- personal video recorders and set-top boxes for HDTV, which tend to replace VHS tape by introducing short term time shifting ability to TV,

- video game boxes,

- data storage for handheld devices (camera, camcorder, mp3 players, ...),

New consumer applications market was only 1.5 M units in 2003, but is expected to be over 50 M units in 2005, and probably equal to PC market some time in the future.

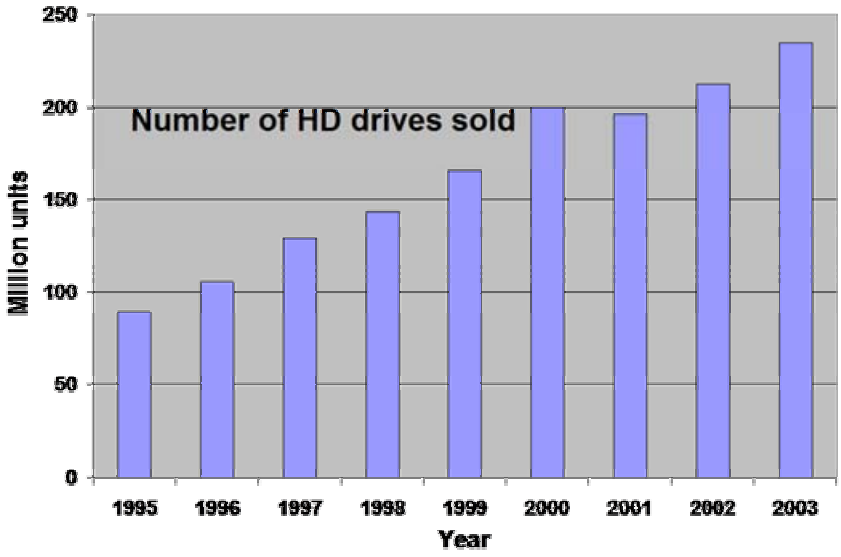


Figure 2

As mentioned above, 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 companies remain: Seagate, Western Digital, Maxtor, Hitachi GST, Toshiba, Fujitsu et Samsung, and for heads only: TDK/Headway and Alps. However the desperate need for breakthroughs can make a start-up very successful at securing intellectual property to sell it to majors.

The role of Europe

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

If we consider the possibility that existing European companies may participate to future disruptive evolutions of the technology, then:

- 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 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…

Other SMEs or start-up could take part to major breakthrough evolutions

2.3.1.2 – Tape Storage

Tape storage market is rapidly changing due to severe competition with hard disk and optical storage, even on the 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.in² but only on an area of a few in^2, tape has only 0.5 Gbit/in² areal density but on 10 000 in² 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. 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 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. So major improvements are also needed in tribology.

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, 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 this imperfect support. Increasing areal storage density requires 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 and companies, 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. 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. 3). 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 any other technique, remaining much less than 1 US$/Gbyte when hard disk backup can cost 10 US$/Gbyte. So tape data storage will go on, and predictions for 2004 expect recovery after several years of decline (cf Fig. 4) and throat cutting prices (cf also: www.storagesearch.com).

Expected global market in 2004 should reach US$ 5.9 B, splitted in 25% media, 36% drive, 39% automation. 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.

Finally, despites increases in number of units sold, revenue increases will probably wait for one more year in a very competitive market.

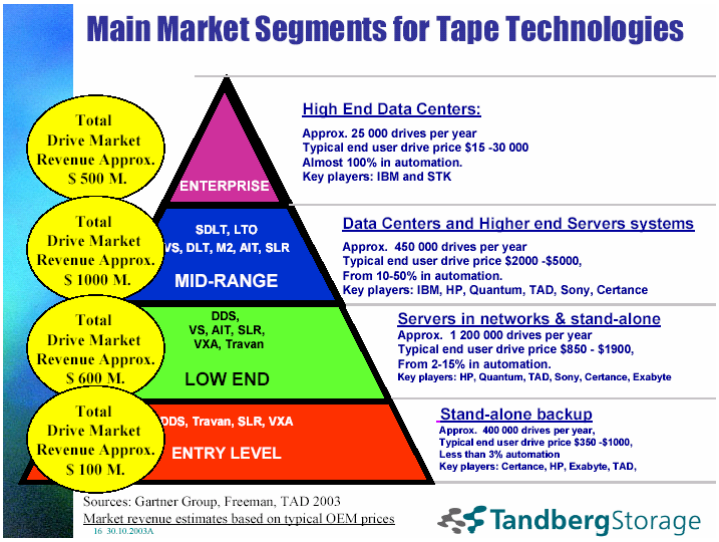
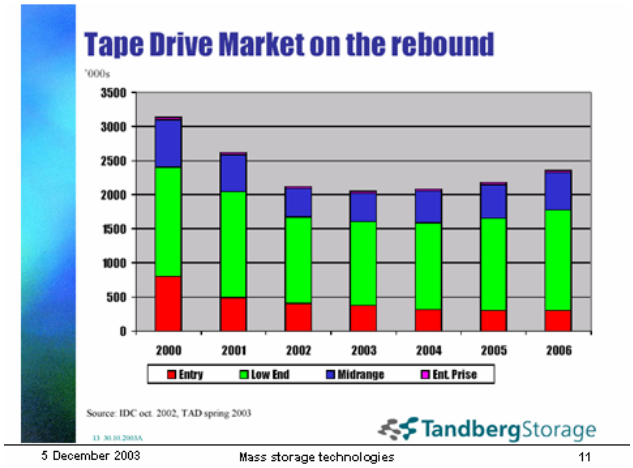


Figure 3 (@Tandberg Storage)

Figure 4
(© 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, 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 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.

2.3.1.3 – Magnetooptical 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, and specifically for perpendicular recording.

In terms of evolution, a magnetic winning option 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 removability.

Status of the market

MO discs production totalled ex factory revenues of only US$ 330M in 2003, compared to US$ 2.2B for hard disk platters, US$ 1.5B for tape media or even US$ 3B for Flash memories.

Data storage accounts for only one third of this number, continuing a decline initiated in 2000 due to the competition with rewriteable CD, 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 growing presence in EU. Beginning of 2004 SONY is shipping 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.

The role of Europe

Europe has long held a strong position in research with Philips and Thomson. However it seems that Philips has just stopped research on MO recording, despites some success in MAMMOS technology.

MPO (F) is still producing MO discs.

The EU project MAMMOSIL gathers 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.

2.3.1.4 – Research opportunities in mainstream magnetic storage technologies

As we tried to demonstrate above, all magnetic technologies are now requiring major technological improvements and even breakthroughs, *linked more and more to nanotechnologies*. This puts increasing pressure on research. Besides, constant increase in storage needs is bound to continue, and *storage is becoming a critical market for high technology development*.

In the mean time European industry is nearly absent (hard disk, MO storage) or weakened (tape), in a very competitive business where there is not much room for new major companies.

But 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 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, that can then sell to majors. Research should also help existing European companies to regain 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.

The above considerations should lead the way for European Union to 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.

2.3.2 Emerging magnetic recording technology: magnetic random access memory

The interest for non volatile solid state storage was already presented in part §2.1, where Magnetic Random Access Memories (MRAM) technology was also rapidly presented as one of several candidates for disruptive evolutions. But solid state portable mass storage, today and tomorrow dominated by the Flash memory, will not be the only application of non volatile solid state memories if they can compete in performances with other RAM memories such as DRAM

and SRAM. Energy savings for instance would be huge if computers could be turned on and off within microseconds or less, without losing information.

Non volatile information storage has been brought up to very high technological levels by hard disk storage, where GHz operation and extreme areal densities have been achieved. 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 in 1975 by another European scientist), provided the vertical miniaturizable 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 met 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

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.

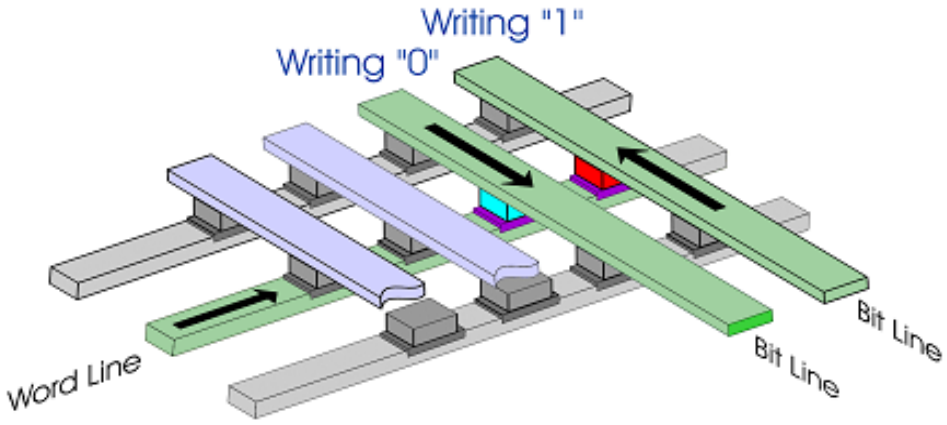


Figure 5
(© S.S.P. Parkin, IBM)

Such MTJ cells are then placed at the cross-points of a dense array of perpendicular conducting lines, such as shown on figure 5. This is the standard *"cross-point"* architecture.

In conventional writing processes current pulses are sent through two perpendicular lines, and the resulting field is high enough to 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 (ΔR/R~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 6.

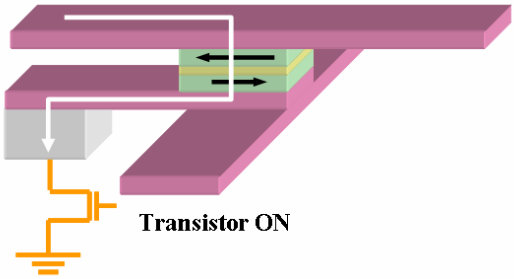


Figure 6

Finally, Figure 7 shows a scheme of the integration of the MTJ in the MOS technology, corresponding to the first 1 Mbit demonstration chip presented by Motorola in June 2002. One interesting observation is that the MTJ is made after completion of the MOS part (above metal level M4), 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), but will limit the high temperature back end annealing usual for finishing MOS chips. 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. Then one can hope to pile up

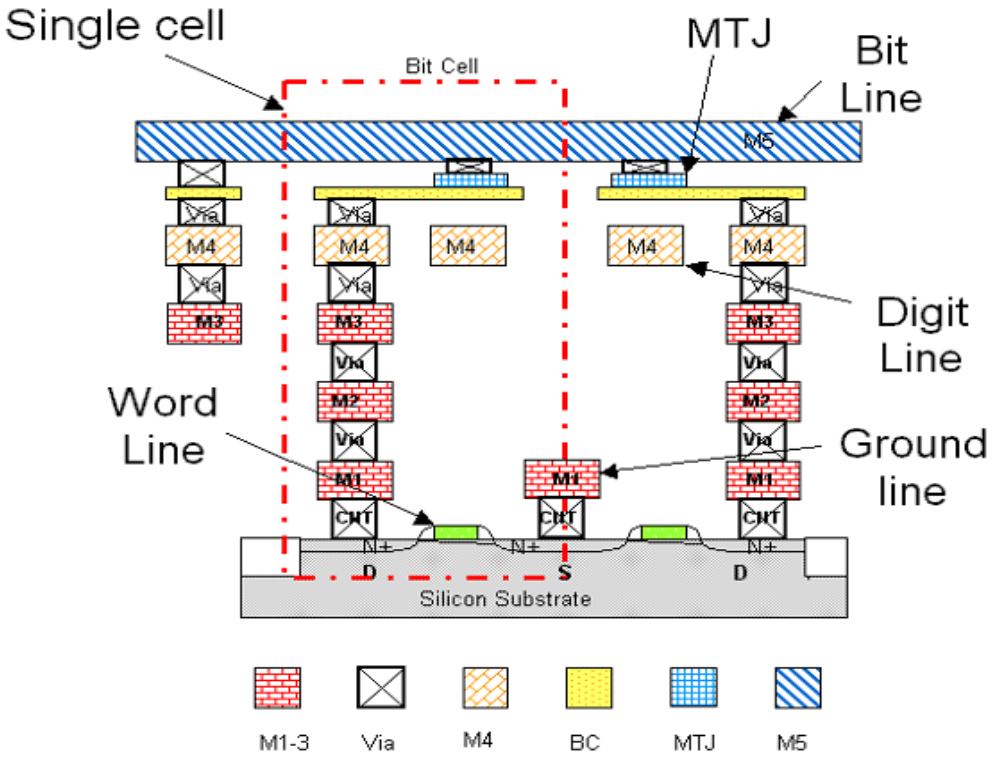


Figure 7:
(© Motorola)

several layers of memory arrays such as the one on Figure 5, on top of a CMOS level that would contains the memory controller logic. Very high 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 increase the tunnel magnetoresistance by something around an order of magnitude at least, although schemes have already been proposed for current MRAMs. This passes through new developments in material studies, such as half metallic ferromagnetic metals (with 100% spin polarization), or new devices such as spin filters, where the non magnetic insulting 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, and mostly by European laboratories, but only at very low temperatures.

- the writing process described above will suffer severe drawbacks at high densities. Electromigration limited 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 and thermal stability.

- today tunnel barrier I is made of less than 1 nm thick of Al_2O_3, to reduce the resistance area product down to level compatible with MOS technology. However resistance is still high and further thickness reduction looks as an impossible challenge, so new oxides with lower barrier height are actively looked for.

As a whole, today's technology, with some continuous improvements such as the one recently introduced by Motorola in its 4Mbit demonstration chip, are expected to hold for the next generations of MOS technology until the 65 nm node, and for the embedded memory application. Beyond that node, or for mass storage applications, research innovations 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 transfer to F1 magnetization of transverse spin angular momentum from the electrons injected through the MTJ. Proposed in 1996 by two US theoreticians, this process has been demonstrated in 1999 on Co/Cu/Co pillars, and more recently on MTJ cells. 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

Nearly all major semiconductor companies throughout the world are intensively competing to bring the first generation of MRAM product to market, maybe as early as 2004. But Intel and HP for instance seem to follow different paths (respectively phase change and ferroelectric RAM).

Several have issued demonstrations, but the two most advanced seem to be:

- Motorola, 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 fast access time (precise value not published).

- 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.

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 1μm^2, DRAM cells are in the 0.2 μm^2 range, and NAND Flash cells around 0.045 μm^2.

So published demos show only limited performances, but one has to keep in mind that only 8 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.

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 reversed:

- 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 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.

- several start-ups are created throughout Europe, to provide innovative developments in parallel with the R&D efforts in major companies.

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 there 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.

2.4 EMERGING TECHNOLOGIES

2.4.1 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. 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. 2.4.1. 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, at a recent INSIC meeting in the USA, a density growth rate of around 30% per annum was suggested 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. The most optimistic forecasts coming out of the hard disk industry itself see a possibility, but a hugely challenging one, of disk based storage at 50Tbit/sq.in., using heat-assisted magnetic recording and self-assembled arrays of 2.5nm-sized FePt particles. It is unlikely that magnetic recording, in a format that we might recognise today,

can extend to the truly nanoscale where individual bits occupy nanometre or sub-nanometre regions. Certainly, hard disk recording with atomic-level storage seems a very remote possibility. From such a perspective it therefore seems appropriate to look at alternative approaches to the conventional hard-disk format that do have reasonable prospects for nanoscale, and even molecular or atomic, surface storage. One such approach is of course scanning probe 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?' Here, a variety of mass-storage alternatives are discussed that may be suited to the low-power, high capacity needs of un-tethered, mobile applications, and may also be capable of providing the huge density requirements foreseen for 10 to 20 years time.

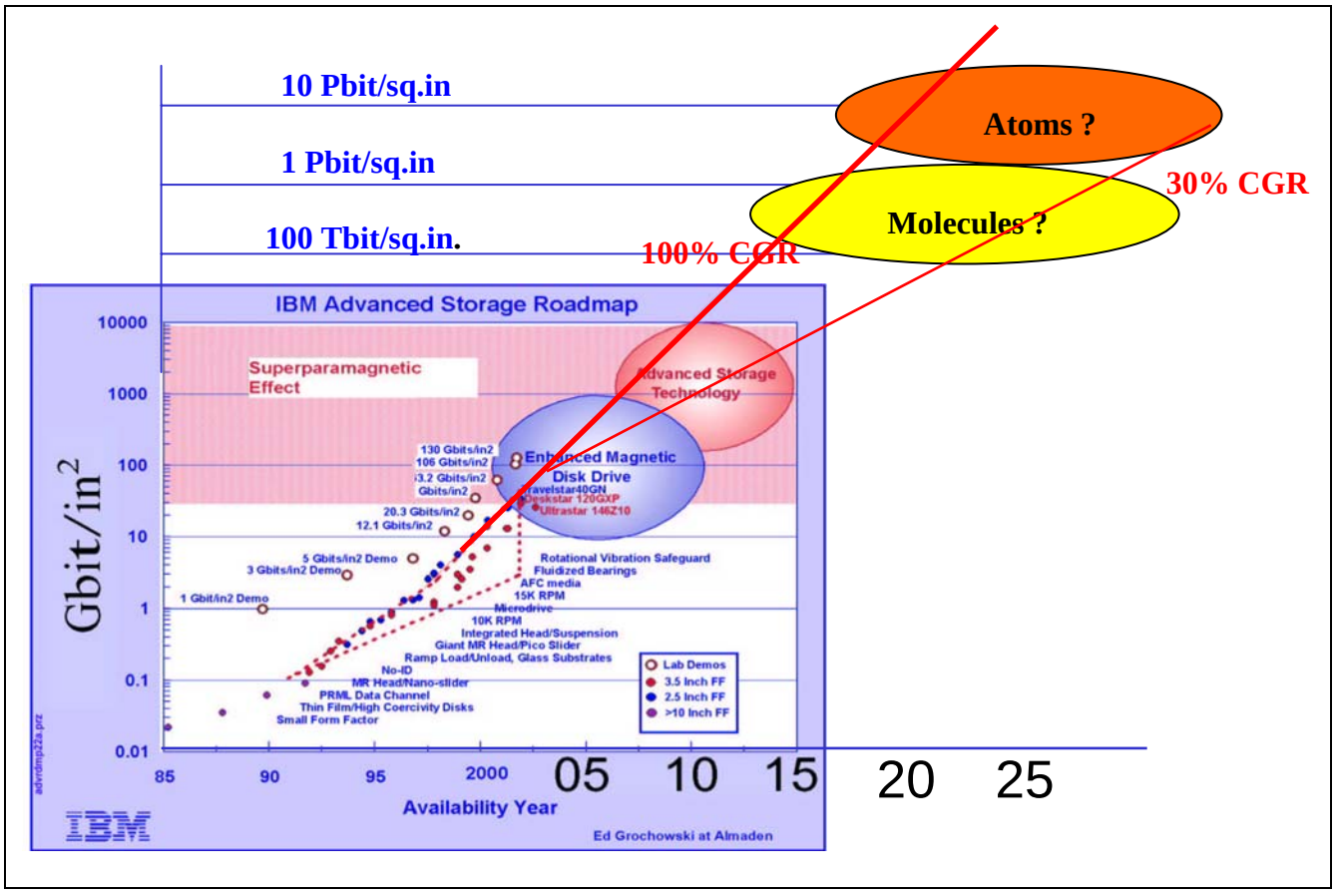


Fig 2.4.1: The IBM storage density roadmap extended to 2025. Two compound growth rates in density are shown; 100% CGR corresponds to growth rates achieved in recent years, 30% to the lower limit of what might be expected in the future in light of the super-paramagnetic limit and the

need therefore to introduce perpendicular and maybe heat-assisted magnetic recording technologies.

2.4.2 Possible alternative technologies

2.4.2.1 Scanning-probe-based storage

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 much-publicised IBM Millipede system showed a way in which data rate could be raised to usable levels. As is now well known the Millipede uses a two-dimensional array of (heated) AFM-type tips to write and read data in a polymer medium. Early work used a 32x32 array of tips to provide data rates in excess of 1 Mbit/s coupled to storage densities in the hundreds of Gbit/sq.in. More recently, over 1Tbit/sq.in has been demonstrated and arrays with 64x64 tips have been fabricated. The write and read mechanisms in the Millipede are thermo-mechanical in origin. To write a bit (illustrated in Fig. 2.4.2a), an electrically heated AFM-type tip is pressed (with forces in the nanoNewton range) against the polymer storage medium to produce a nanoscale (down to 10nm in size) indentation. To read a bit, the heated tip is scanned across the indentation and the amount of heat loss, which varies depending on whether a pit is present or not, is sensed by measuring the electrical power needed to maintain the tip at a constant temperature.

The Millipede system thus offers high areal storage density, a small form factor, and low power consumption, making it attractive for many mobile applications. Several GBytes of capacity could be offered in a format much smaller than say the IBM Microdrive (see Fig 2.4.2c), while the use of a sizeable tip-array ensures a decent data rate to go with the high capacity.

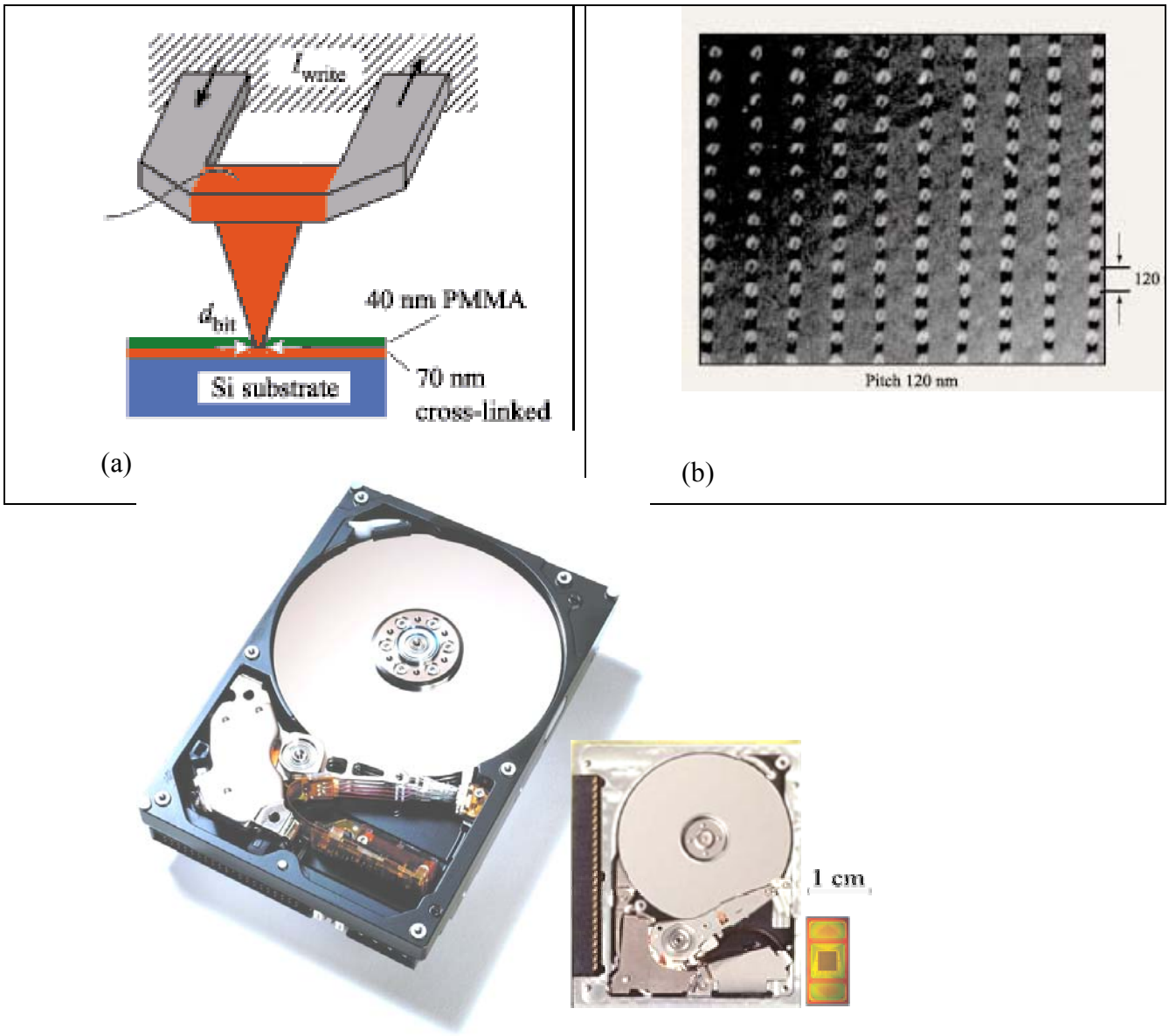
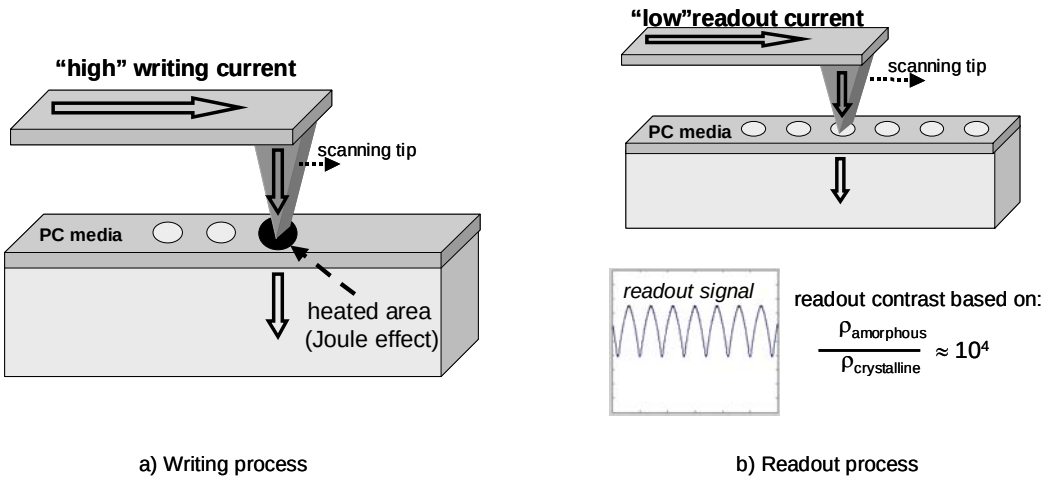


Fig. 2.4.2: (a) the Millipede writing process - temperatures > 400°C are used, (b) 40nm pits formed in a polymer medium and (c) relative sizes of 2.5 inch, 1 inch (IBM Microdrive) hard disk systems and basic Millipede hardware

Of course IBM is not the only group working in probe-based storage. 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. Figure 2.4.3 shows the basic record and readout mechanism of the InProM system. Experimentally

recorded 20nm in a GeSbTe medium are also shown. Although these results were achieved in a modified commercial scanning probe microscope, the InProM approach is, like the IBM system, suitable for a dedicated 2-D probe array to provide a high data rate to go with the high density capability. Indeed, since the phase-change material used for InProM is inherently re-writable, it has considerable advantages compared to the Millipede. Furthermore, since heating in the InProM system arises directly from electrical current flowing through the medium (rather than indirectly by heat diffusion from a heated tip as in the Millipede system), it uses considerably less power than the IBM approach (0.1nJ writing energy per bit compared with 10nJ per bit for Millipede). Thus, the InProM based approach may offer superior erasability and superior power consumption with no loss of performance in terms of density or data rate.



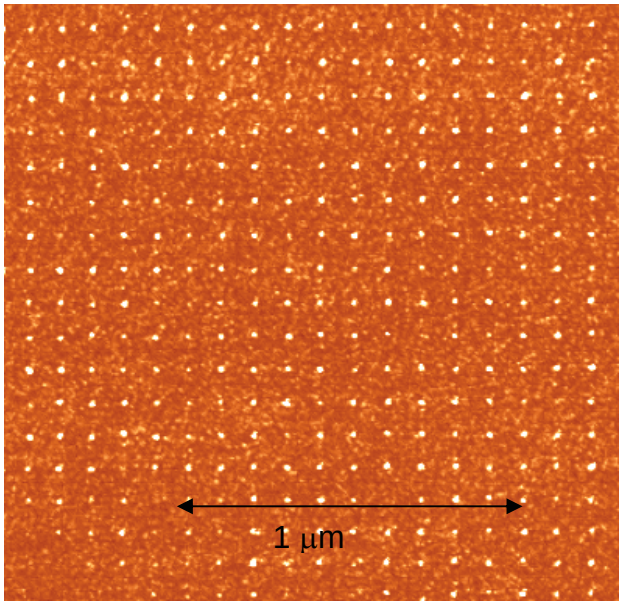


Fig. 2.4.3 Schematic of the electro-thermal scanning probe storage system using phase-change media. High writing current induces crystallisation by Joule heating (top left). Readout process uses much lower current to sense the different electrical conductivities of amorphous and crystalline phases (top 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

The importance of scanning probe-based approaches to the future development of data storage is also evidenced by the seriousness with which research into such systems is being pursued outside the EU. In the USA, for example, Hewlett-Packard have been working on what they term 'atomic resolution storage (ARS)' for several years (Chaiken et al, paper HH1.9, MRS Fall Meeting, Boston, Dec 2003). The HP-ARS system utilises electron beams from an array of field-emitters to heat a phase-change medium (in fact a Se-based material), inducing crystallisation. Readout of the crystallised areas is by a form of 'electron beam induced current', a technique used in electron microscopy circles for many years. Although the HP approach is termed 'atomic resolution', written bit sizes in results presented publicly have been in the 25nm range. At the recent MRS Fall Meeting (Boston USA, December 2003) it was also unofficially announced that the ARS project was being scaled back due to a combination of financial and technical reasons – rumoured to be associated with problems fabricating the field-emitter array.

It is also well-known that Seagate Research, Pittsburgh, are actively investigating probe storage options (http://www.seagate.com/newsinfo/newsroom/papers/D2c25.html); few details are emerging except that phase-change media are one of the options being studied. A group at Carnegie Mellon University Pittsburgh is pursuing MEMS-based probe storage for application to a new type of 'highly integrated information processing and storage system', for a plethora of intelligent processing tasks (see http://www.chips.ece.cmu.edu).

Interest in probe-based storage is also evident in Japan. A group at Tohoku University, in collaboration with the Corporate R&D Laboratories of Pioneer, has developed an electrically-based approach using a ferroelectric storage medium (Cho et al, Nanotechnology, 14, 637-642, 2003). Here, writing is achieved by switching the electric polarization in the ferroelectric storage layer; reading is by sensing a low-order (of the permittivity tensor) non-linear dielectric constant whose sign depends on polarization direction. The group has demonstrated writing, reading and erasing. Storage densities in excess of 1 Tbit/sq.in have been achieved. To date results for a single tip only have been announced (as opposed to use of a 2-D tip array), and single-crystal ferroelectric thin films (not particularly easy or cheap to produce) have been used as the storage medium.

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 (Barrett and Quate, J Appl Phys, 70, 2725, 1991), anodic oxidation of titanium with an AFM probe (Cooper et al, Appl Phys Lett, 75, 3566, 1999), an AFM-

based memory with polyimide Langmuir-Blodgett films (Yano and Ikeda, Appl Phys Lett, 80, 1067, 2002), patterning of magnetic and organic films by 'Dip-Pen' nanolithography (Ginger et al, Angew. Chem. Int Ed, 43, 30-45, 2004). 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).

Volumetric storage

An alternative approach to achieving ultra-high storage density and capacity is of course to store data throughout the volume of a storage medium, rather than on a single surface. Such an approach already exists to a limited extent in the multi-layer DVD-ROM and dual-layer Blu-ray optical storage formats. However, the goal of many has for a long time being the realization of a true-volumetric storage technique combined with a parallel, page-addressed recording and readout processes. This might then provide the 'ideal' combination of huge capacity (of the order of TBytes), small form factor, no (or very few) moving parts, together with ultra-high data rates coupled with a parallel processing capability.

Routes followed to realize such goals have been many and varied. These include two-photon storage in polymers (Rentzepis et al, Optics Communications, 223, 61-66, also http://www.Call-Recall.com) and proteins (Birge et al, J Phys Chem B, 103, 10746-10766, 1999, also http://www.biofold.net)), fluorescent multilayer disks (Constellation 3D – now out of business), spectral hole burning (Maniloff et al, MRS Bulletin, 46-50, 1999), photon-echo storage (Cornish et al, Opt Lett, 25, 1276-1278, 2000), and, last but not least, holography.

The holographic approach is perhaps the most widely known, and indeed was predicted to be in use by 2010 in the last (now somewhat dated) version of the OIDTA Roadmap for optical storage (see Fig. 2.4.4a). It is attractive since it offers a potential volumetric density that scales with wavelength as $1/\lambda^3$, coupled with fast parallel access (potential data rates of Gbits/second order). The widespread commercial introduction of holographic storage has been so far frustrated by a lack of suitably cheap and rugged system components (lasers, light modulators, detector arrays etc) and suitable media (with the necessary sensitivity, dynamic range, environmental and thermal stability etc), in particular for re-writable memories. Much of this is now changing, driven in part by development of suitable system components in other areas of technology (for example cheap CMOS detector arrays for digital cameras), and by new research on suitable media. Perhaps

the most advanced stage of commercialization has been achieved in the USA by InPhase Technologies (http://www.inphase-technologies.com), who have developed a two-chemistry photopolymer holographic material, initially for write-once applications only. The company is currently researching re-writable materials, and has grand plans for the application of its holographic memories (see for example Fig. 2.4.4b). However, no products yet exist and their potential impact on the market is uncertain.

2.4.3 The European perspective

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:

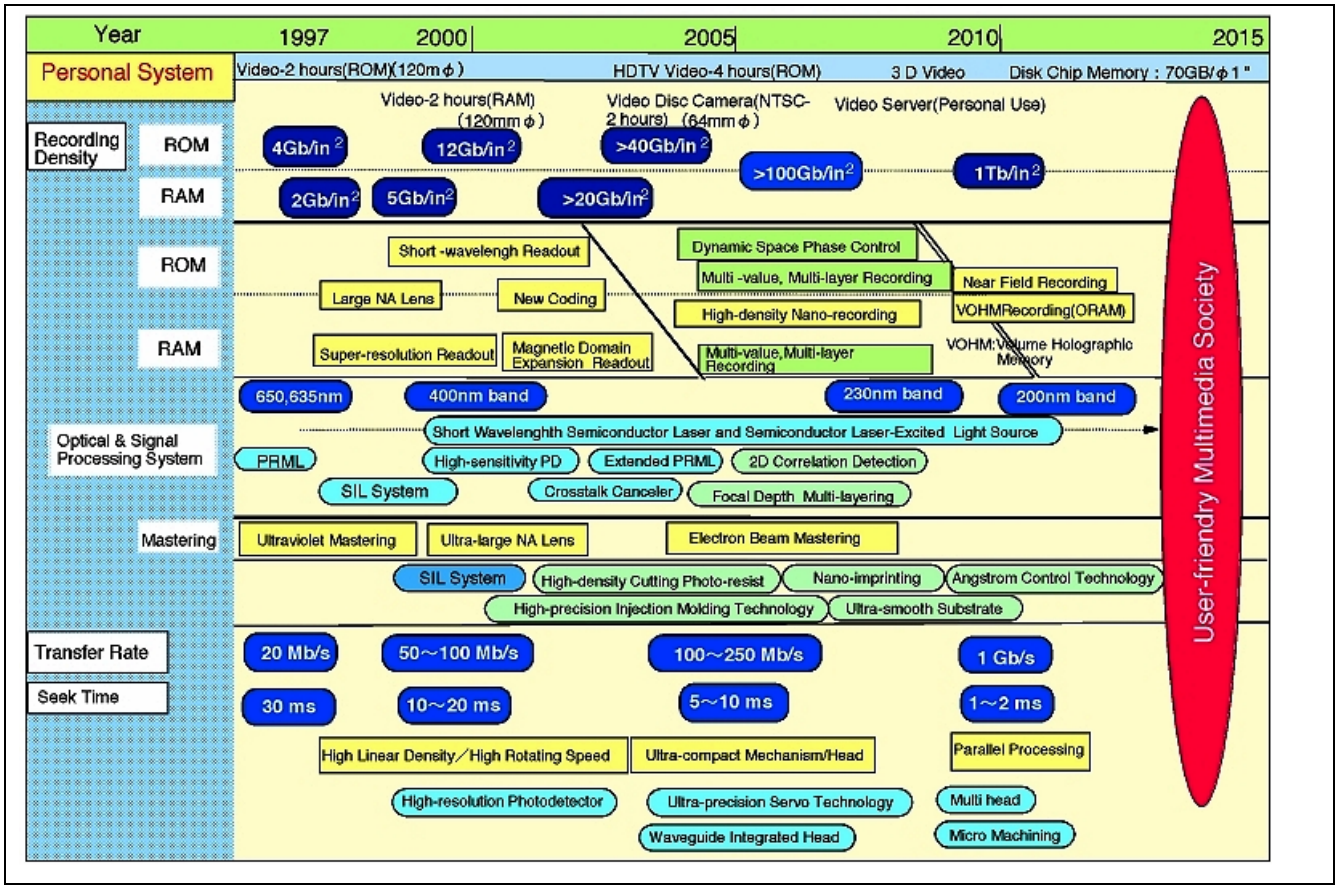
Technical challenges facing conventional hard disk recording arising from the super-paramagnetic effect, coupled with the inability (in anything like its current form) for hard disk recording to write and read data on the truly nanometric scale.

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'.

The route for the development of next generations of hard disk systems is already quite well defined. It is expected that the current longitudinal recording mode will give way to perpendicular recording on high anisotropy media in the next few years, and push densities towards the 500 Gbit/sq.in to 1 Tbit/sq.in range. Still further ahead there will be the real ruptures, with the need for heat-assisted magnetic storage to enable the recording on (as yet to be developed) ultra-high anisotropy media (probably made from self-assembled magnetic arrays of near-identical particles). It is questionable whether the EU can or should play any central role in ongoing hard disk technology developments. Clearly the centre of gravity for this work lies in the USA and, since the sale of IBM hard drive business to Hitachi, Japan. However, as pointed out in the part of this report dedicated to magnetic memories, existing EU companies or start ups could take advantage of major breakthrough to come back in this area – especially as the European Research Community is especially strong and innovative in magnetism and will provide the needed template. This implies

that there is probably no real hope to catch up with incremental developments, but that real technological ruptures are worth investigating (self organized media, media and heads for magnetic probe recording, innovative MRAM paths…).



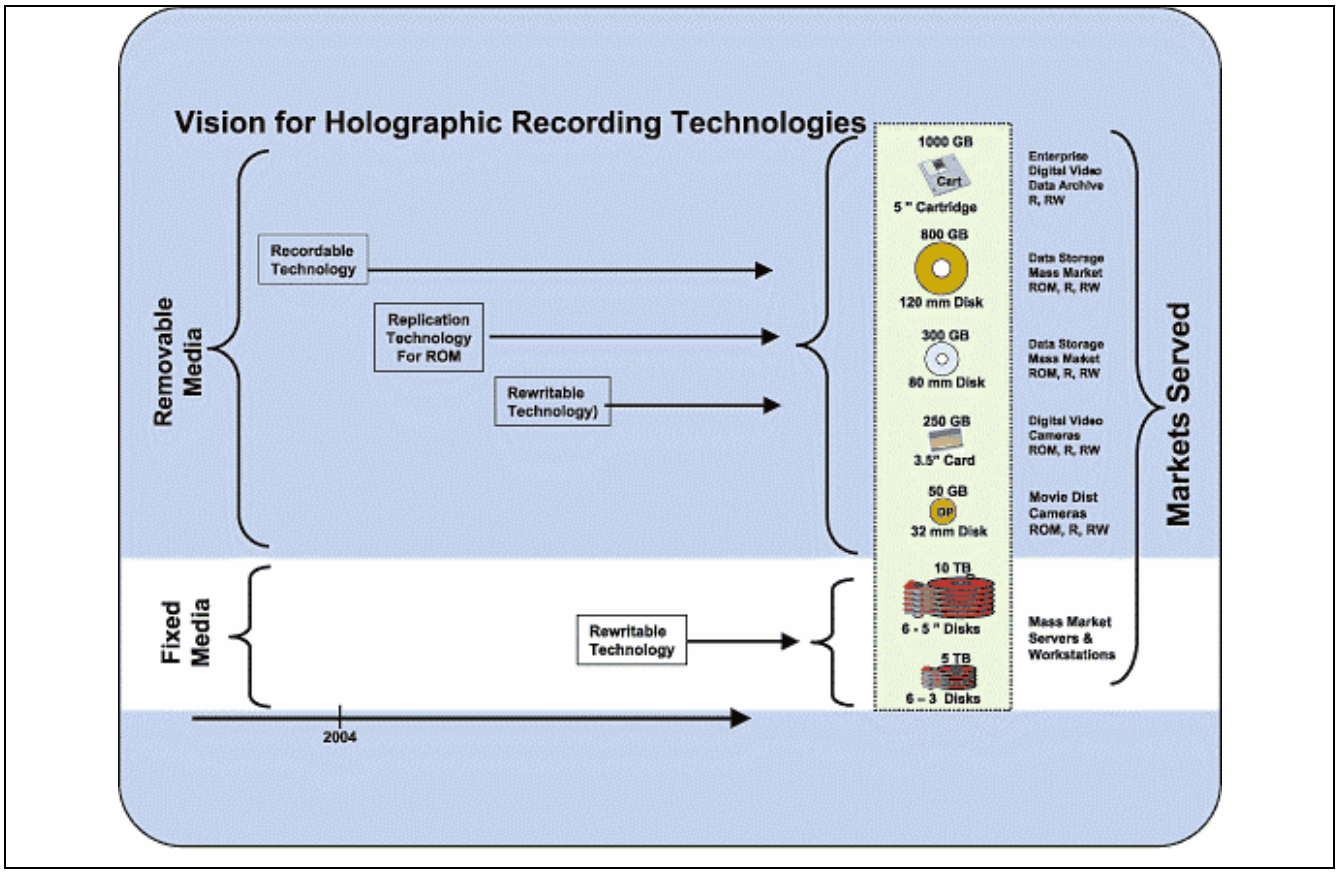


Fig. 2.4.4 (a) (top) OIDTA optical storage roadmap (1997) and (b) possibilities for holographic storage according to InPhase Technologies Corporation (http://www.inphase-technologies.com)

A more sensible and potentially successful route would be to target specific data storage needs that cannot be addressed easily by the hard disk solution. In particular, the development of high capacity, ultra-low-power, compact data storage formats for the burgeoning 'un-tethered', or mobile, technology market will provide an excellent vehicle for investment. 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 favor 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 storage 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. 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.

3. 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 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.

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.

4- **CONCLUSION and RECOMMENDATIONS**:

These synthetic recommendations are based on both the individual expertise of the four rapporteurs and on the answers provided by about 20 European actors in Mass Storage Technologies. They are made under the responsibility of the IMST workgroup, and do not bind any company or laboratory. They aim at maintaining and developing European R&D at the top international level, in order to preserve competitivity in current areas of activity and to secure the best possible positions in emerging areas. The European dimension is at the core of our technical and scientific analysis.

Solid state memories:

- Flash memories technologies following the ITRS roadmap and breakthrough for new materials, integration, new designs, reliability, adaptability
- Disruptive technologies matching the CMOS technology and going beyond the Flash performances, with breakthrough in new materials, integration, design, reliability, scalability, adaptability (PC-RAM, Fe-RAM, organic RAM).
- 3 D technologies and new design
- Very low cost technologies for low tech end users

Optical memories:

- Optical systems for near field recording: new materials, new optics, micro actuators MEMs based (heterogeneous technologies)
- Light sources R&D for deep UV LD (see SUVOS US program)
- System: data rate, multiplexing, new concepts for signal processing, new systems (cards or others)
- 3D optical storage: new materials, new integrated systems, multilevel, holography; fluorescent technologies
- User friendly low-cost replicated optical memories

Magnetic memories:

- Towards 1 TBit/sq.in: materials breakthrough (self organized media, nanoimprint ..), micro actuators, head technologies (heterogeneous technologies).
- Systems
- Breakthrough in tape technologies: data transfer, reliability, low cost
- Microelectronic magnetic logic: pure logic, solid state memories (M-RAM)

Emerging technologies for memories application:

- Over 1 Tbit/sq.in: probe storage, nanoscale handling technologies, new materials, new systems, new micro actuator (heterogeneous technologies), systems (multiplexing, coding..)

- 3D: polymer materials, complex heterogeneous micro systems (optical and mechanical).

The amount of activity of the European industry is not the same in each of these technical and scientific fields, neither is the level of the European basic research with respect to the international competitors. In addition, some of these areas involve very big companies and other smaller ones. Taking also into account the maturity of each field, we can propose different types of research programs to ensure the best possible efficiency of the European research effort :

Solid state memories:

- STREP for flash technology
- IP for the disruptive technologies taking into account M-RAM, PC-RAM, Fe-RAM and organic.
- STREP for 3D technologies and low cost memories.
- NoE for new materials, design and systems.

Optical memories:

- IP on new technologies for optical discs (near field systems, deep UV solid state lasers, micro actuators, multiplexing, new concepts for signal processing)
- STREP on 3D holography: new systems (MEMS, MOEMS, heterogeneous technologies) and new materials
- NoE on new optical systems and materials

Magnetic memories:

- NoE on new materials, new systems
- IP on new designs for M-RAM (see Solid State)
- STREP for magnetic logic
- STREP for disruptive media designs such as self organized
- STREP for tape recording breakthrough

Emerging memories:

- STREP for probe recording technologies and materials (IP may be suitable soon here), handling nanosized particles, new systems and design, integration for MEMS…
- NoE on 3D new technologies

The estimation of such a R&D program is of 4 IP, 15 STREPS and 4 NoE. The total budget would be roughly in the range of 120 M€.

We can target benefits for:

- Memory business in general (solid state, optical, magnetic) and European industry (both big existing companies and new start ups)
- Generic technical breakthrough towards nanotechnologies system handling and knowledge (likely to benefit out of the area of Mass Storage Technologies)
- Microelectronics new systems and new materials use
- New MEMS and MOEMS application systems
- Knowledge in the future new heterogeneous technologies (Si, glass, plastic, ceramics, organics).
- Better organization and higher efficiency of the European research

IMST workgroup can play a role by providing a synthetic view of the evolution of these technologies through a SSA project.

APPENDIX 1:

MAIN EUROPEAN PROJECTS ON NON VOLATILE MEMORIES

(PROBABLY NOT EXHAUSTIVE / OVERVIEW MAINLY ON SOLID STATE)

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.

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.

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).

IST/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

INPROM : Integrated Probe Memories (concluded) – probe recording on magnetic and phase change media

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

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.

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 a 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.