Public Progress Report - 1st October 2006 to 30 September 2007

ProTeM

Probe-based Terabit Memory

Project Summary

Title - ProTeM - Probe-based Terabit (per square inch) Memory

Aim - to develop probe storage micro-nano techniques and systems for ultra-high-capacity, low power, small form-factor memories, with a particular focus on archival and back-up applications

Vision - Ultra-high storage densities (1 to 10 Tbit/sq.in.), ultra-high capacities (20 TBytes in CD-sized area), media and system lifetimes and data rates suitable for archival and backup storage

Partners - IBM Zurich GmbH, CEA-LETI, ST Microelectronics, RWTH-Aachen, Plasmon Data Systems Ltd, Arithmatica Ltd, University of Twente, FhG - ISIT, University of Exeter, ALMA Consulting Group

Co-ordinator - Professor C David Wright, University of Exeter (David.Wright@exeter.ac.uk)

Project Funding - 5,298,510 €

Project Budget - 9,627,544 €

Project start date - 1st October 2006

Project Duration - 4 years

Project number - FP6-2005-IST-5-34719

Website www.protem-fp6.org

Introduction

Data storage technology is at a critical point in its development. A combination of two very strong driving forces is emerging:

- a **'societal'** one demanding **smaller, lower-power, higher-capacity yet reliable memories for a plethora of multimedia, communication and digital archiving applications.**
- and a **technological** one brought about by challenges facing **conventional storage techniques as they approach formidable barriers to continued improvements (see Fig 1)**: the *superparamagnetic limit* for magnetic storage, the *diffraction limit* for optical storage, and *device scaling limits* in solid state (Flash) storage. Difficult challenges therefore face conventional memories as they strive to reach ultra-high storage densities.

The time is hence ripe for **new**, **emerging technologies to enter the storage field**. One such emerging technology is **probe storage**, which has enormous potential to satisfy future needs for **ultra-high-capacity, non-volatile, low-power, low-cost, write-once and re-writable memories**.

ProTeM aims to capitalise on this opportunity for emerging technologies by developing probe storage micro-nano techniques and systems for very high-density mass storage in a small size and with high performance. The primary objective is to develop and exploit the necessary research and technology to address the needs of the important data storage domain of ***digital archiving*** (initially for large-scale administrations, financial institutions, health systems, etc., but also with potential future interest for smaller-scale archiving for perhaps accounting and legal departments, engineering and design offices, publishing houses etc., even maybe for personal digital archives). The professional data storage market (archival and backup) is a strong one in Europe, with key internationally-leading industrial players (notably Plasmon and Tandberg, but with a host of specialist players - Xendata, Xyratex, O-Mass, HiStor, M5Data...) based here for both research/development and manufacturing activities. It is therefore a mass storage area in which the EU can and should compete globally in terms of both intellectual property and EU-based manufacturing. For archival applications reliability, data integrity and media longevity (in both write-once read-many (WORM) and re-writable (R/W) formats) feature much more prominently than in other storage sectors and professional archiving addresses different cost/performance requirements compared to standard consumer applications. ProTeM aims to meet all these archival requirements (density, capacity, data rate, longevity...) through innovative probe-storage solutions.

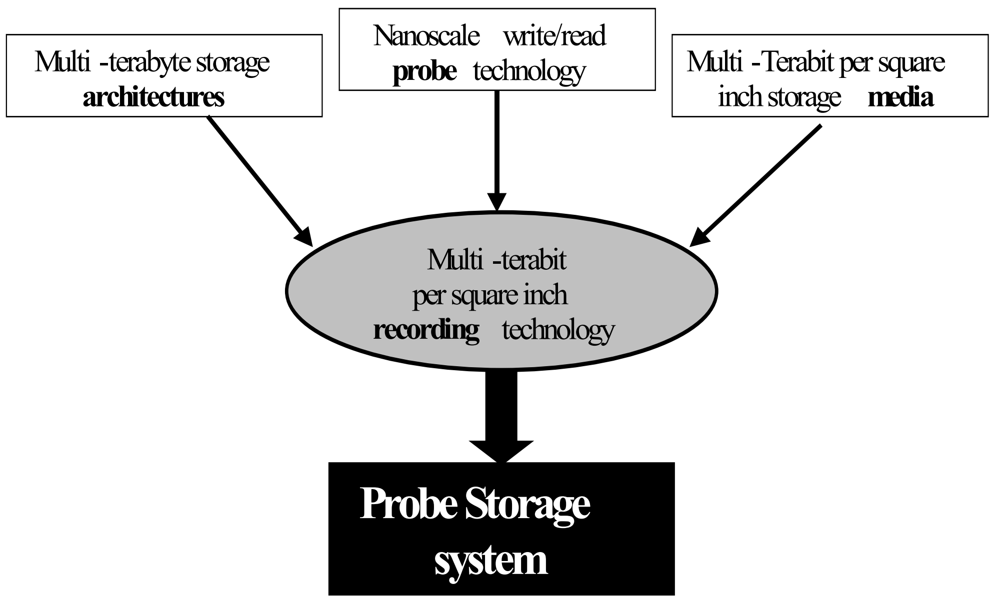
Although our primary objective is the research and development of the science and technology of small, low-power yet ultra-high capacity ***archival*** probe-storage systems, it is most likely that the solutions we develop will have significant applications in other important data storage sectors. If sufficiently high data rates can be achieved then we should also be able to address the backup market. Ultra-high capacity low-power mass storage systems would also be very attractive for several high-technology sectors (e.g. aeronautical, transport, nuclear, space…) - again areas in which the EU is strong enough to compete globally and should remain so. ProTeM's research of new WORM and R/W probe storage techniques will also undoubtedly benefit the mass-market area of the storage of multimedia content and storage for mobile applications - an activity likely to be of large-scale commercial benefit for consumer electronics, even if mass-market economics often dictate manufacturing outside of the EU and in the 'developing world'.

A key requirement for any viable ultra-high density mass storage device or system is the ability to reduce the interaction volume between the 'head', used for writing and reading of data, and the storage medium. Probe-storage meets this requirement by using techniques adapted from scanning probe microscopy (SPM) to detect and modify on the nanoscale various material properties. The relatively slow write/read process of such a SPM systems, which depends on the scanning speed, can be compensated to some extent for storage applications by the parallel operation of a two-dimensional array of tips.

While the principle of probe storage has been demonstrated, notably by several of ProTeM's partners (IBM , CEA, Twente, Exeter) but also by other groups around the globe, much research and development remains in order to reach the goal of fully-functioning probe-storage devices and systems suited to real storage applications and markets and capable of financially-attractive commercialisation. Europe currently leads the world in probe-storage research, and ProTeM will capitalise and exploit this lead to deliver probe-storage devices and concepts with a real chance of commercialisation in targeted storage sectors (primarily the high-cost niche area of **professional archive storage**, but with significant impact also expected for **data storage in the backup and high-technology sectors**, and also possibly the **multimedia content and mobile devices** area).

ProTeM will thus research a variety of interlinked science and technology areas - e.g. micro/nano fabrication, nanoscale thermal and electrical processes, materials research, micro-actuators, signal processing, micro-systems integration, storage systems architectures - in order to successfully develop multi-Terabyte integrated probe memories, primarily for professional storage (digital arching) applications. This is of course not a straightforward task, however, our consortium brings together some of the world-leading groups in probe storage and related technologies, guaranteeing that our goals should be achieved.

ProTeM is organised into four main technical workpackages, as shown below.



Summary of the objectives and main achievements of the first 12 month period

The main objectives for the first year and progress towards their achievement can be summarised as:

- to establish effective management and administration procedures for the project

Suitable procedures and management tools are in place; the consortium is working very well together.

- to determine target specifications for a probe-based archival storage system

Detailed targets for such a system have been devised after extensive consultations between all partners

- to identify five alternative physical system architectures suited to probe-based archival storage

Five such architectures have been identified - disk, plotter, tape, juke, stodisk - and these are now undergoing detailed modelling and analysis.

- to advance the state of the art for microprobe design to deliver high endurance, high-speed, high-sensitivity, low power thermo-mechancial and electrical probes

New thermo-mechanical probe designs with much lower (than previous designs) thermal and mechanical time constants have been devised, modelled and fabricated. New encapsulated electrical probe designs have been devised, modelled and fabricated; the aim is to provide high resolution electrical probes capable of writing/reading bits at densities > 1 Tbit/sq.in while at the same time having high endurance.

- to begin synthesis and characterisation of polymer media optimised for high-density (>1 Tbit/sq.in), high-speed (> 1Mbit/s writing per probe) and excellent bit retention

A number of polymers have been synthesised and excellent progress has been made with the fabrication of ultra-smooth polymers suitable for very high densities.

- to begin development of WORM phase-change media for use with electrical probes

The properties of a suitable layer stack (carbon/phase-change/carbon/silicon) and individual layer properties for the provision of WORM phase-change media have been determined.

- to begin the development of RW phase-change media for use with electrical probes

Material compositions likely to deliver slow crystallisation speeds necessary to allow for amorphisation by probe have been identified and methods for measuring crystallisation velocity have been put in place. Preliminary investigations of two approaches - self organisation and lithogaphy - to the patterning of phase-change media have been carried out.

- to develop a suitable test-station for performance of write/read/erase tests

A specialised test-stand for probe storage application has been set-up at IBM in Zurich (for testing polymer media) and know-how transferred to CEA-LETI (for testing phase-change media)

- to begin development of physically realistic channel models for probe storage

A simple channel model for thermo-mechanical/polymer systems has been implemented and suitable detection schemes for such a model have been tested; a new 'probabilistic threshold detection' scheme has been devised and shows good performance. Models have been developed for write/read/erase and noise processes for electrical/phase-change systems and a preliminary study of read channel properties for such systems carried out.

- to publicise the project and make links with other similar projects worldwide

A public website has been created (www.protem-fp6.org). A link with the IMST2007 conference (www.imst.org) was made and specific training sessions on probe storage were delivered (via special tutorial session at the conference). A publicity flyer has been produced and other dissemination activities carried out (papers presented at IMST2007 and IPSW2006).

Highlights of 1st Year results by Workpackage

Workpackage 1 – Multi-terabyte storage architectures (leader Plasmon)

We have identified likely system specifications for a probe-based archival system and these are shown in Table 1.

Specifications from a user perspective

System Specifications		min	max	Units/comment
System Capacity		200	1000	TB
Transactions per day	read	2000	10000	per 24 hours
	write	1	10000	per 24 hours
streaming data rate	write	100	250	MB/sec
	read	100	1000	MB/sec
worst case access	write	1	10	secs
	read	1	10	
Typical file size for transfer		2KB	100MB	
Random access within one media unit			1	second
number of concurrent read users		10	1000	
number of concurrent write users		1	10	
Purchase cost		100,000	200,000	Euro
TCO		25,000	100,000	Euro per year
Power consumption			300	watts
Hardware Maintenance Cost		4	8	%age of purchase cost
Software Maintenance Cost		5	15	%age of purchase cost
"Spin-up" time			5	seconds

Media Level Specification		min	max	Units/comment
Media unit capacity		2	100	TB
Media read cycles	read	10^6		over media life
Media purchase cost (200TB)		6000	40000	(USD/Euro) 0.03 - 0.20 /GB
media life		20	50+	years (at 50C)
Sector size			8	k
RW cyclability		10,000		overwrites
Operating temperature range		-5	45	C

Table 1.1 Overall system specification for an enterprise type (probe storage) archive system.

Five physical architectures with the potential to provide such system specifications have been suggested, and these are shown in Figure 1.

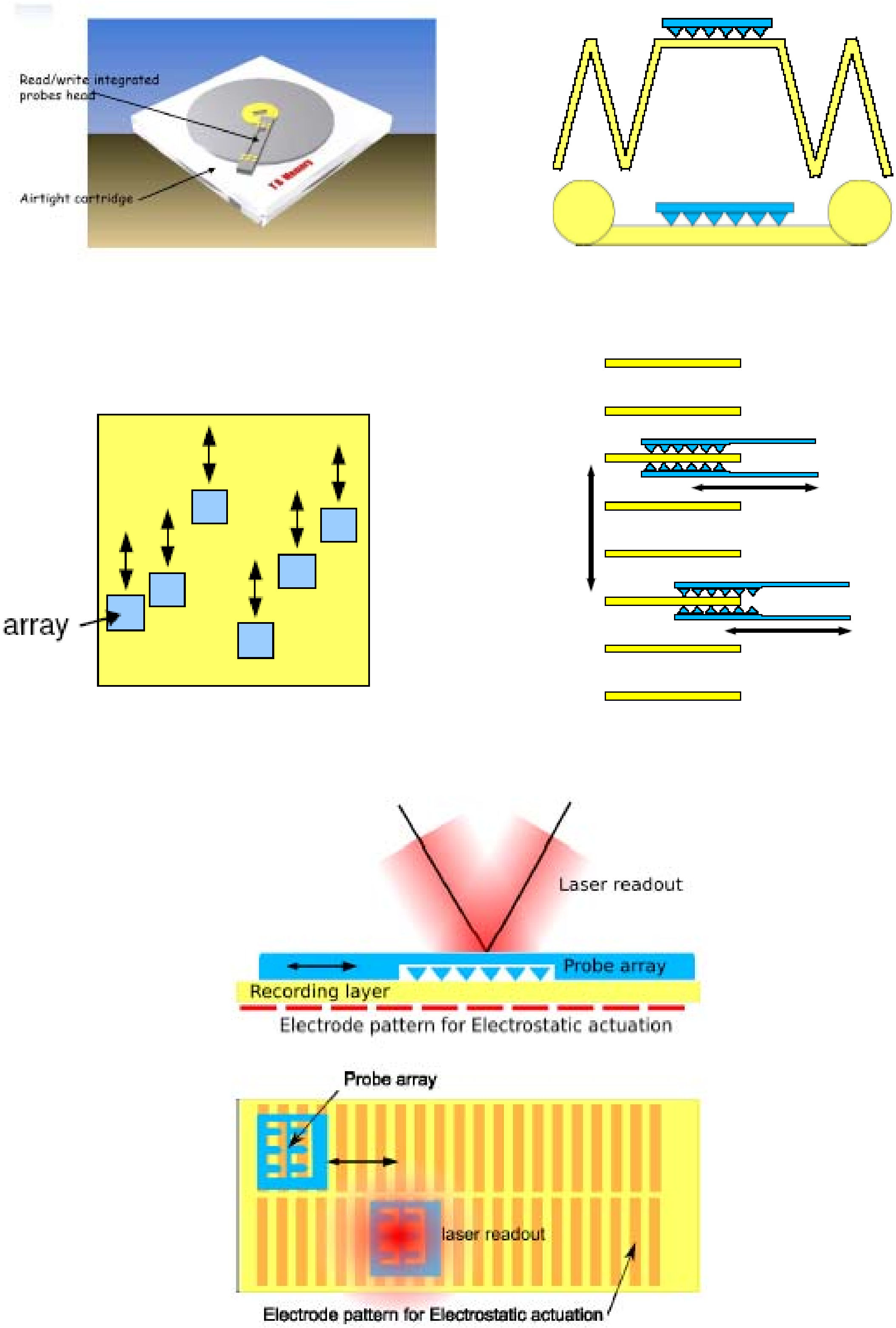


Figure 1 Illustration of DISK (top left), TAPE (top right), PLOTTER (middle left), JUKE (middle right) and STODISK (bottom) concepts.

Workpackage 2 – Nanoscale write/read probe technologies (leader IBM)

The objective of work package 2 is the development of advanced microprobe technologies with high endurance, high speed, high sensitivity and low-power consumption for polymer and phase-change media applications.

New designs of ***thermomechanical and piezoelectric probes***, see Figure 2, have been investigated by *IBM and FhG-ISiT (Itzehoe)* focusing on fast thermal and mechanical time constant. Finite element simulation has been carried out to optimize the designs. The simulation highlighted the trade-off between power consumption and speed which will need to be carefully analysed for the system performance optimisation in terms of power, parallelism and data rate.

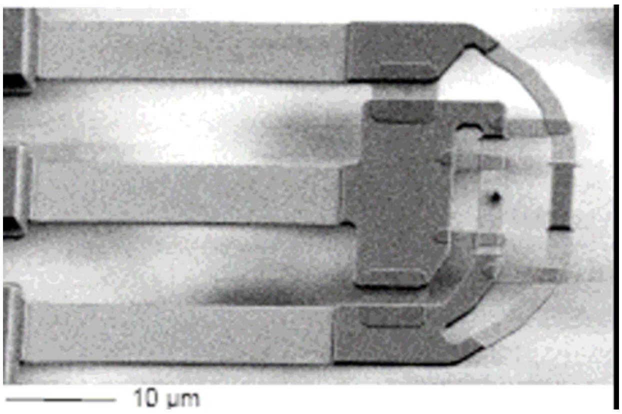


Figure 2 SEM image of new ProTeM power efficient thermomechanical cantilever

New designs for electrical probes, see Figure 3, have also been made by *IBM* and *CEA* working together to provide high resolution readout combined with high endurance (low wear) tips.

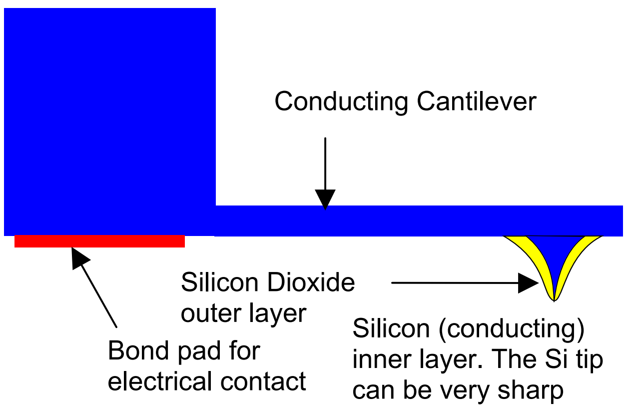


Figure 3: Schematic of ProTeM new electrical tip design

Workpackage 3.1 – Multi-Terabit per square inch storage media: Polymers (leader IBM)

The objectives of this work package are to identify, synthesize, and characterize polymer media that are optimized specifically for storage applications. Key requirements are high data density >1Tb/in^2, high writing speeds >1Mbit/s, and excellent bit retention characteristics (ultimately >50years).

The main focus was on demonstrating high speed writing capability of thermo-mechanical recording. Previous work in the "Millipede" storage project showed that high densities up to 4Tb/in^2 and bit retention exceeding tens of years can be achieved with highly cross-linked high temperature polymers based on poly-aryl-ether-ketones. We have demonstrated in this first 12 months period that high speed writing at 1 Mbit/s data rate per lever is feasible using thermo-mechanical recording. This result constitutes an important milestone for archival storage applications as this data rate is more than one order of magnitude larger than what has been previously reported.

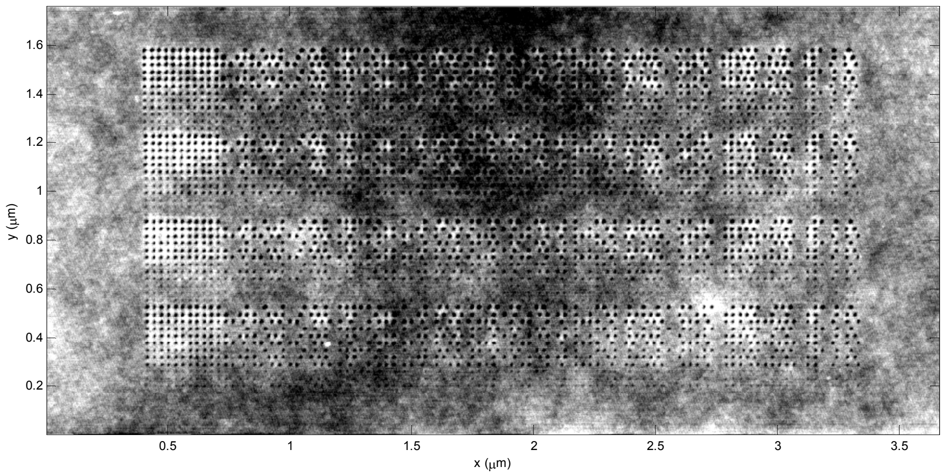


Figure 4 – Grid of bits indented in a low cross-linked polymer. Each one of the four blocks was written at a different temperature, respectively from bottom to top, 100C, 230C, 367C and 500C. Within each block, the force is increased after each three lines. Respectively, 85nN, 105nN, 125nN and 145nN.

Since in thermomechanical probe data storage the information is stored in a change of the topography of the polymer medium surface, a dominant noise source is the natural surface roughness of the medium. In order to increase the areal densities to values of more than ~2 Tbit/in^2, the depth of the indentations approaches 1nm, which is comparable to the surface roughness noise. Therefore improving the surface roughness on the polymer medium is a major target. *IBM* have thus developed a process which leads to a 'flat' media with a highly improved surface roughness.

Workpackage 3.2 – Multi-Terabit per square inch storage media: Phase Change Media (leader CEA-LETI)

The overall objectives of WP3.2 are to assess and to design phase-change media for archival probe storage applications by exploring two types of media. ProTeM partners *CEA-LETI, RWTH-Aachen, Plasmon, ST Microelectronics and Exeter* are working collaboratively to achieve these objectives.

The type consists of a WORM media which will be developed using the pre-existing know-how from previous InProM project and partners expertise on WORM phase-change materials. The initial media stack will be further optimized by evaluating basic material characteristics, testing the media performances assessing wear, cyclability and retention aspects, and refining media and process accordingly.

A second type of phase-change media will be investigated to evaluate erasability with such materials, so providing a R/W capability.

ProTeM phase-change media requirements are shown in Table 2.

Data storage specifications	WORM media	RW media
Density	≥ 1 Tbit/in^2	≥ 1 Tbit/in^2
Read cyclability	10^6 - 10^{10} per bit	10^6 - 10^{10} per bit
Write cyclability		10000 per bit
Read speed	≤ 1μs	≤ 1μs
Writing time	≤ 1μs	≤ 1μs
retention	20 – 50 years @ 50°C	20 – 50 years @ 50°C
Operation temperature range	-5°C – 45°C	-5°C – 45°C

Table 2 Specifications for the phase-change WORM and RW media

A basic media stack suitable for WORM applications is shown in Figure 5

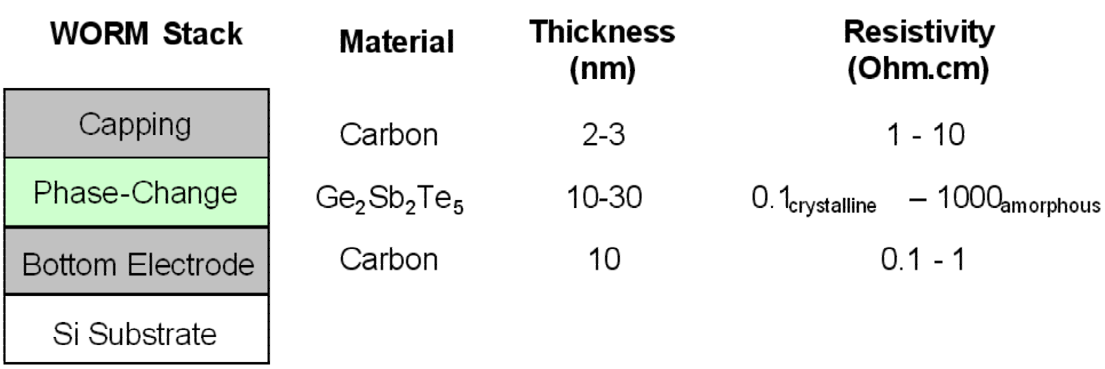


Figure 5 Initial WORM media description

To provide RW functionality ProTeM partners *CEA-LETI, RWTH-Aachen, Plasmon and Exeter* are also investigating a number of alternative approaches using phase-change media including (i) slow-crystallisation speed materials and (ii) patterned media.

In recent years a considerable number of phase-change materials have been identified for rewriteable optical and electrical data storage. $Ge_2Sb_2Te_5$ has become a kind of industrial standard material and is widely used as a reference. However for the probe storage application, phase-change materials used as continuous rewritable media ideally should exhibit, when compared to $Ge_2Sb_2Te_5$, a lower crystallization speed, a reduced resistivity contrast and a higher crystallization temperature. Hence conventional phase-change material know-how established in the past decade can only be employed to guide selection strategies. In the first year of ProTeM we have successfully identified a number of potential chalcogenide materials that are likely to exhibit low crystallisation speed and/or low amorphous/crystalline electrical contrast.

For the patterning of phase-change media we have investigated self-organized phase-change nanostructures based on de-wetting processes of very thin films, the idea being to create nanoballs of PC materials from a continuous layer. The study of the self-assembly upon annealing of nanometre-sized metal and semiconductor islands has also become important recently as it is an attractive method for producing nanoscale devices without expensive lithography and could be explained by a thermodynamic analysis of the structures. An example of this approach is shown in Figure 6.

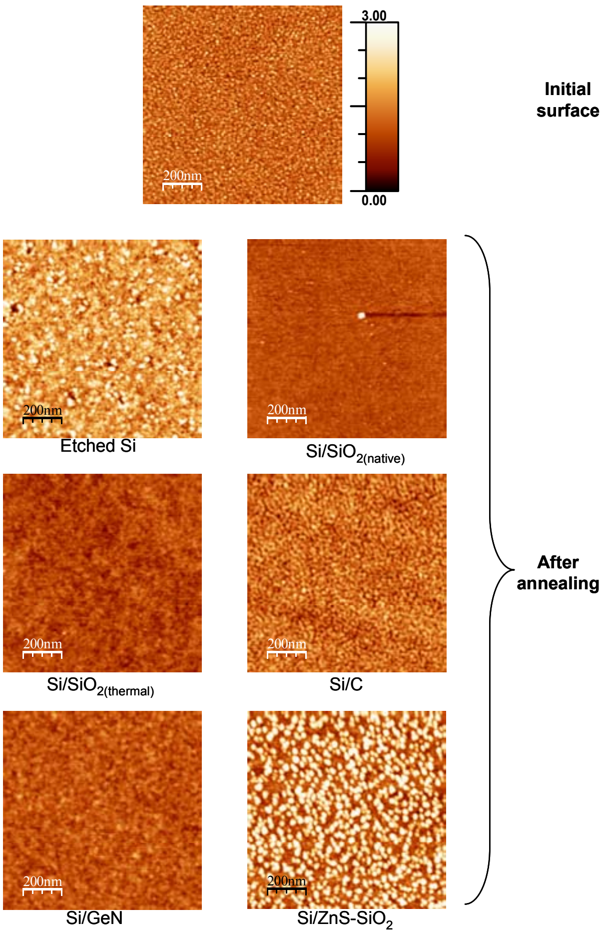


Figure 6 AFM images (1μm×1μm scan) of samples Substrate/4nm GST after annealing at 700°C for one hour for different substrates. The initial surface is also shown at the top as a reference. The height scale is the same in all the images.

Workpackage 4 – Multi-terabit per square inch recording technologies (leader Arithmatica)

A specialized testing environment has been set-up by *IBM* for the purpose of probe-media testing and the development/testing of new recording schemes. The test-stand comprises a custom-made cantilever-tip holder, a set of piezoelectric scanners for 3-D actuation together with associated controllers for closed-loop positioning, a data-acquisition system, a custom-made analog front-end PCB, and an anti-vibration table. The new test-stand has the capability to control the timing and data flow between electronics and the tip, and to generate voltage pulses directly or trigger signals for external arbitrary waveform generators in order to drive the microprobe (e.g. voltage pulses for heating thermo-mechanical probes). Know-how on test-stand development has been shared by *IBM* with *CEA-LETI* so that the latter may use similar approaches to the testing of phase-change media.

IBM, Arithmatica and Exeter have also developed write/read/erase and channel models for both thermomechanical-polymer and electrical-phase-change probe storage systems. Figure 7 shows an example of bit-writing simulation in phase-change media.

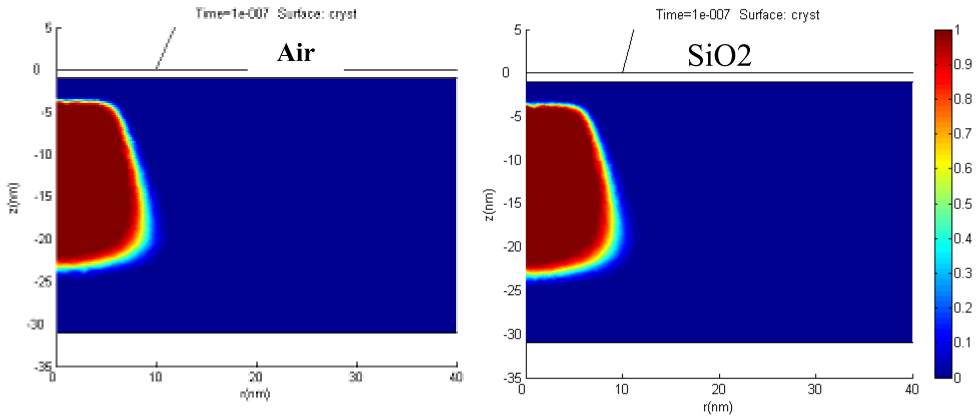


Figure 7 3-D write model: (Left) Standard tip and (Right) Encapsulated tip. Crystallized bits in 30 nm thick GST layer - 4V tip-substrate, 100ns pulse, 1 nm capping layer with 100 $(\Omega.m)^{-1}$. This simulation includes the convection and radiation factor. The heat transfer coefficient is 10 W/(m^{2}K)

Arithmatica and *Exeter* have together investigated the bounds on the amount of coding needed to create a reliable probe-based archival storage. The corresponding storage device needs about 2000 probes per storage platter to meet the throughput requirements (100 MB/s). The complexity of such a device makes the life-time requirement (50 years) a very challenging one indeed. In our study we investigated various scenarios for trading capacity for reliability using redundant probes and/or coding - a typical result is shown in Figure 8.

IBM have developed a model of the read-back waveform for thermomechanical readout from polymer media. Here the signal is created as a linear superposition of impulse responses (Figure 9) corrupted by various jitters. *IBM* delivered this impulse response to Arithmatica, together with the details of the model, allowing *Arithmatica* to integrate this linear model of the Millipede channel into their simulation tool. *Arithmatica* have also developed a non-linear model of the Millipede channel, extending the simple model of non-linear inter-symbol interference developed by *IBM* by introducing jitter noise.

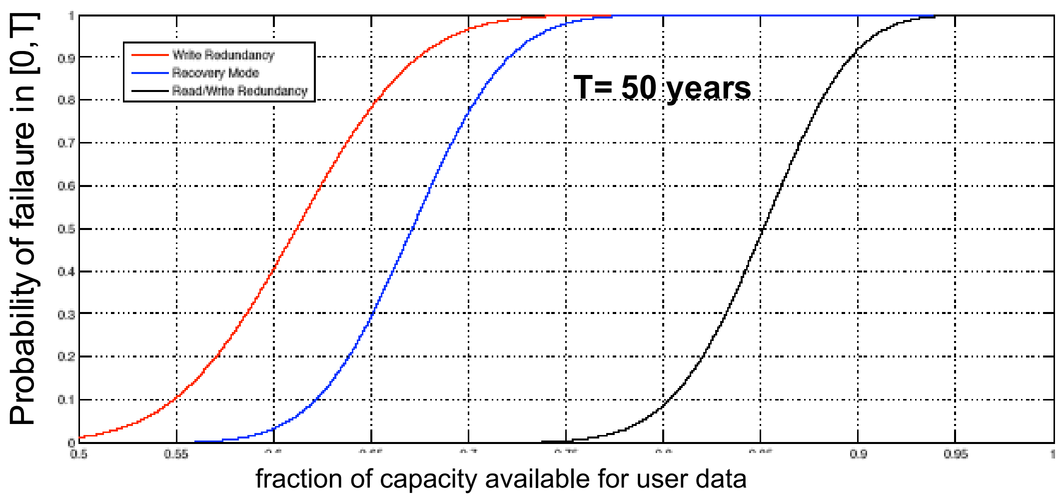


Figure 8 Probability of system failure within 50 years for a 1000 tip array versus fraction of capacity available for storage of user data, including the effects of write redundancy, read/write redundancy and use of 'recovery' mode.

Using readout signal information from experiments and simulations, *Arithmatica* and *IBM* have together developed a soft-output data detector which is well suited to the probe storage channel based on probabilistic message passing. *Arithmatica* performed simulations which demonstrated that this detector can offer 0.6dB SNR improvement in a simplified Millipede channel model. Moreover, *IBM* performed follow-up simulations and found that the BER of the probabilistic threshold detector is the same as BER of the Viterbi detector matched to the non-linear ISI of the Millipede channel.

Within WP4, the *Twente* group has been investigating candidate file systems for probe storage. In the first 12 months they concentrated on the system as a whole to identify objectives and conditions for the subsystems of a probe-based storage system for archival applications. Twente argues the need for a parallel storage system (aka the file system). This file system can retrieve data reliably even when at most **k** out of the **n** available channels fail. The actual details (settings) of the implementation depend on the channel conditions, which include channel/data coding and the ProTeM architecture. Each channel could refer to a single robust device or a channel could refer to a scanner that is part of a device with a number of parallel scanners.

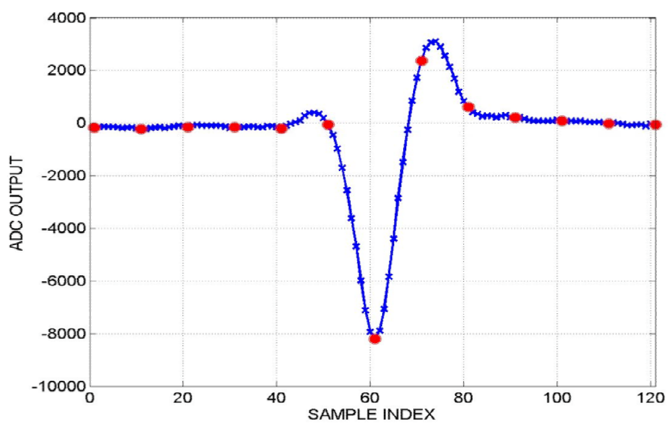


Figure 9 Impulse response for the linear thermomechanical channel. One can see that the writing of a single bit will partially erase the next bit.

Workpackage 5 – Transversal activities (leader Twente)

A market and technical survey of the requirements for archival systems has been carried out by *Plasmon.* This has been used as the background to ProTeM system designs and specifications. An in-depth *training session* on system aspects of probe storage was organised by *Twente* and held in a special session immediately prior to IMST2007 in June 2007. Three presentations were given by experts in the field, two of which by ProTeM partners. The mini-symposium opened with a tutorial by *Abu Sebastian of IBM* on positioning systems, followed by a presentation by *Oleg Zaboronski of Arithmatica* on coding, and finally *Sape Mullende*r of *Lucent* closed the symposium with a tutorial on file systems. The complete session was taped on video by the University of Twente, and is available on DVD and via the IMST website (www.imst.org) and the ProTeM website (www.protem-gp6.org).

Two *project websites* have been set up, one for internal, confidential communication and archiving (www.myndsphere.com) by *Alma*, as well as one for the outside world (www.protem-fp6.org) set up by *Exeter*, which also includes the first project newsletter (D5.5) in downloadable form. A project flyer has been prepared by *Twente*, which is distributed amongst interested parties at conferences etc and is available via the public website.