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Project coordinator organisation: University of Exeter

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Introduction and Overview

Aim - the aim of the ProTeM project was 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/in²), ultra-high capacities (2 to 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, Numonyx (originally ST Microelectronics), RWTH-Aachen, Plarion Ltd (originally Plasmon Ltd), Siglead Europe Ltd (originally 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)

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Website www.protem-fp6.org

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 aimed 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 was 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 aimed to meet all these archival requirements (density, capacity, data rate, longevity...) through innovative probe-storage solutions.

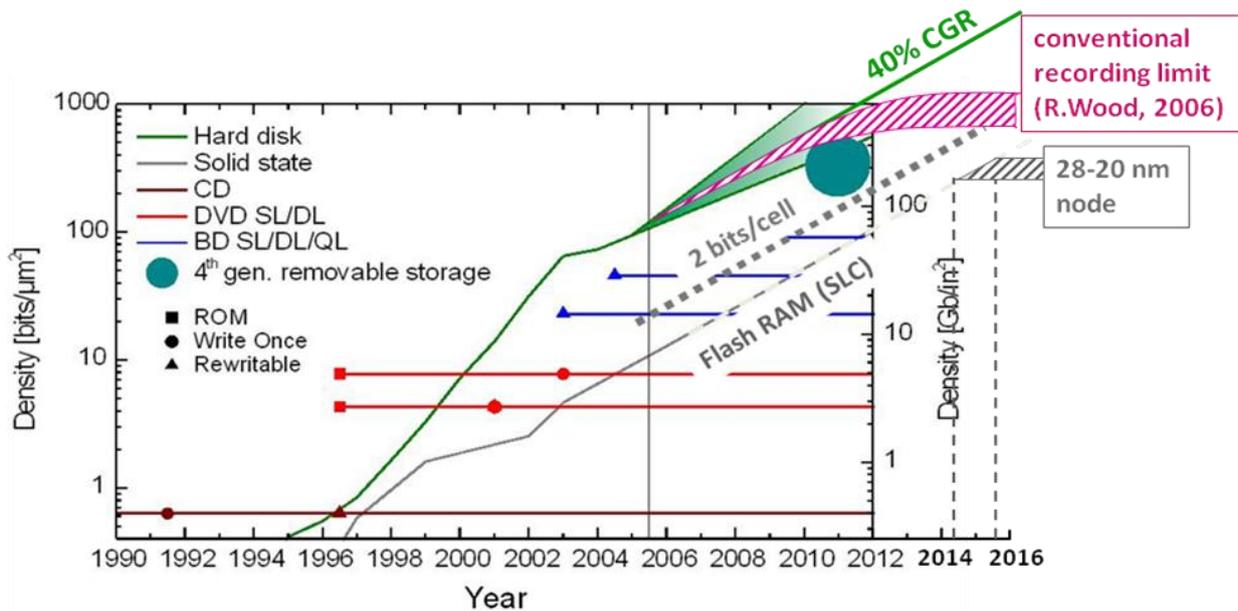
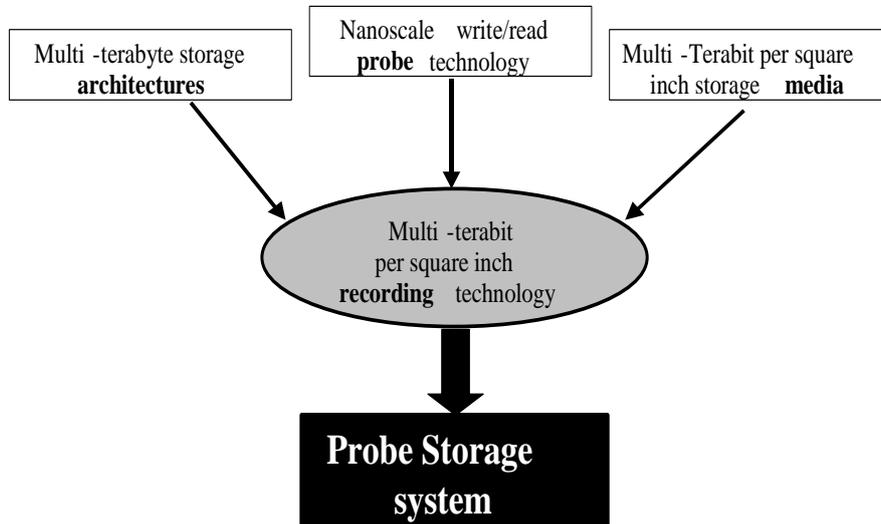


Fig. 1 : Evolution of the data densities for the main technologies for mass data storage. Note that the optical technologies progress by discrete steps at each generation (CD, DVD...) while magnetic media (Hard Disk) and solid state memories (Flash) experience continuous evolutions. (taken from the IMST White Book 2010 edition - see www.wind-fp6.org)

Although our primary objective was 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'.

General project objectives and organisation

ProTeM was organised into four main technical work packages, as shown below.



The main technical objectives of each of these workpackages (as envisioned at the start of the project) are summarised in the following tables:

- **Multi-TeraByte Storage Architectures:**

Targeted objectives
<ul style="list-style-type: none"> • To get an overview of specifications and architectures for various backup and archiving markets • Selection of two positioning system architectures, based on design analysis and testing • Realisation and demonstration of positioning systems capable of addressing at least 100 cm² area, with access times below 1s and 5 nm precision • Data rate: 1 Mbit/second/probe

- **Nanoscale Write/Read Probe Technologies:**

Targeted objectives
Electrical probe and thermomechanical probe with the following specifications <ul style="list-style-type: none"> • Tip radius: <10nm (suitable for multi Tb/in² density) • Tip endurance: depends of the application specification and the array size but should be in the 10¹⁰ event range (read is the limitation) • Single probe data rate: depends of the application specification and the array size but should be in the 1μs range or lower • Single probe read out consumption: sub mW • Cantilever size: 50 to 80 μm (suitable for integration in array with a 100μm or so cantilever pitch) • High manufacturability for production environment

- **Multi-Terabit per square inch Storage Media:**

Targeted objectives

- 1 μ s writing time
- Capability of writing at multi Tbit/in² areal density
- Low media wear compatible with 10¹⁰ reads per bit
- High bit retention >50y @ 50°C
- Write-once media
- ReWritable media: 1000 Rewrite events per bit
- Two generic media approaches

Polymers:

- thermo-mechanical materials
- new organically bistable electrical materials
- new embedded carbon nanotube/polymer materials

Phase-change media

- "True" WORM Phase Change media
- new "slow crystallisation speed" ReWritable media
- new Patterned ReWritable media

- **Multi-Terabit per square inch Recording Technologies:**

Targeted objectives

- Construction of specialised probe recording test stations
- Physically realistic write/read/erase/noise models for nanoscale storage on phase-change and polymer media
- Experimental evaluation of write/read/erase and archival performance of media designs
- Reading electronic module sensitivity: 100nA/V
- Reading electronic resolution: <10nA at 1Mhz Band Width
- Writing electronic module voltage swing +/- 5V
- Writing current >100 μ A
- Slew rate down to 2ns
- Raw error rates < 1E-4 at 1 Tb/in² areal density
- Maximise dB gain through proper read channel design for probe storage system
- Maximise dB gain after ECC through 2D and parallel error correction coding schemes
- Achieve silicon bill of materials cost proportional to today's silicon BOM in archival systems (~20% of drive cost)

ProTeM investigated possible alternative architectures for probe-based archival storage systems and devised a set of typical specifications, from a user-perspective, that a future probe-based archival system might be expected to provide (shown in Table 1). Technical challenges for probe-based storage in meeting such specifications are primarily concerned with three aspects: (i) storage capacity; (ii) write/read speeds; (iii) tip/media longevity. To provide the necessary capacity we need to be able to write and read over a relatively large (storage media) area at very high data densities in the region 1Tbit/in² to 10Tbit/in². To provide the necessary write/read data rates we need to provide a high write/read speed per probe, typically 1 Mbit/s or more, and/or use large 2-D probe arrays. To provide the

necessary longevity we must utilise storage materials with the necessary long-term stability and, importantly, mitigate any adverse effects of tip and media wear. We addressed all these

issues within the ProTeM project, via two alternative routes. The first uses thermo-mechanical probes and polymer media, as pioneered by IBM in their 'Millipede' system. The second route utilises scanning electrical probes and electro-thermal write/read with phase-change media.

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	
Power consumption			300	watts
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 life		20	50+	years (at 50C)
Sector size			8	k
RW cyclability		10,000		overwrites
Operating temperature range		-5	45	C

Table 1 Possible probe-based archival storage system specifications - a driving force for ProTeM investigations

Some selected key achievements (though by no means all achievements) of the ProTeM project are discussed below on a workpackage by workpackage basis. For a fuller description of such results please see the numerous (> 100) publications that have resulted from this project and for which links can be found on the project website www.protem-fp6.org.

WP 1 - MultiTeraByte Storage Architectures

Reliability of archiving systems

Principal achievements

- For the design of an archiving system, reliability is of the uttermost importance. Reliability can either be achieved by realizing a single, extremely reliable system (Tortoise approach) or by combining many, less reliable redundant systems (Ants approach). We have shown that a limited number of redundant systems is sufficient.

Applications of research to technology other than probe storage

- The framework developed in ProTeM is not only of importance to archival storage, but will benefit the design of all systems where reliability is an issue.

Long range positioning

Principal achievements

- We investigated two routes towards large area probe storage. The first route is to combine the actuators with the probe arrays (Ants approach). This requires that actuation is wireless. In ProTeM we demonstrated long range electrostatic actuation of insulating objects at a macro scale.
- The second route to use one single array, and a conventional long range motorized scanner (Tortoise approach). We have constructed the first prototype of such a system, and demonstrated that positioning is sufficiently accurate. In principle, a system like this would be suitable for large capacity probe storage

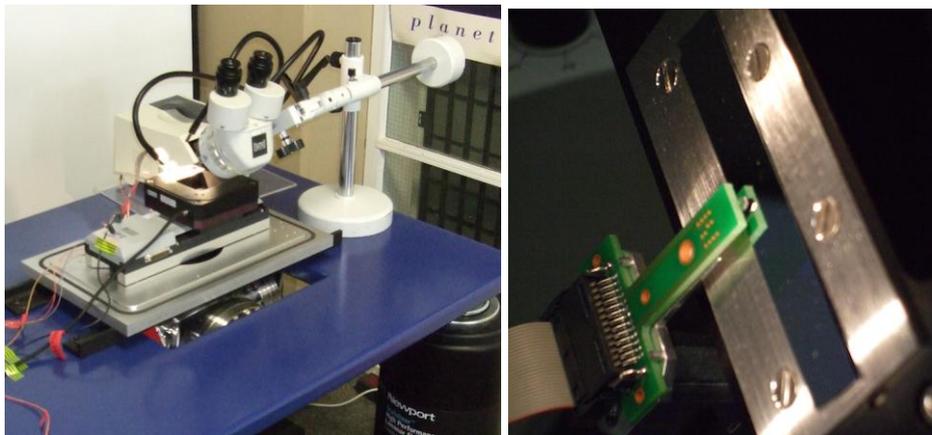


Figure 2 Probe recording setup for 1D arrays with a 10 cm range positioning system. The left image shows a close-up of the 1D array positioned over a recording medium.

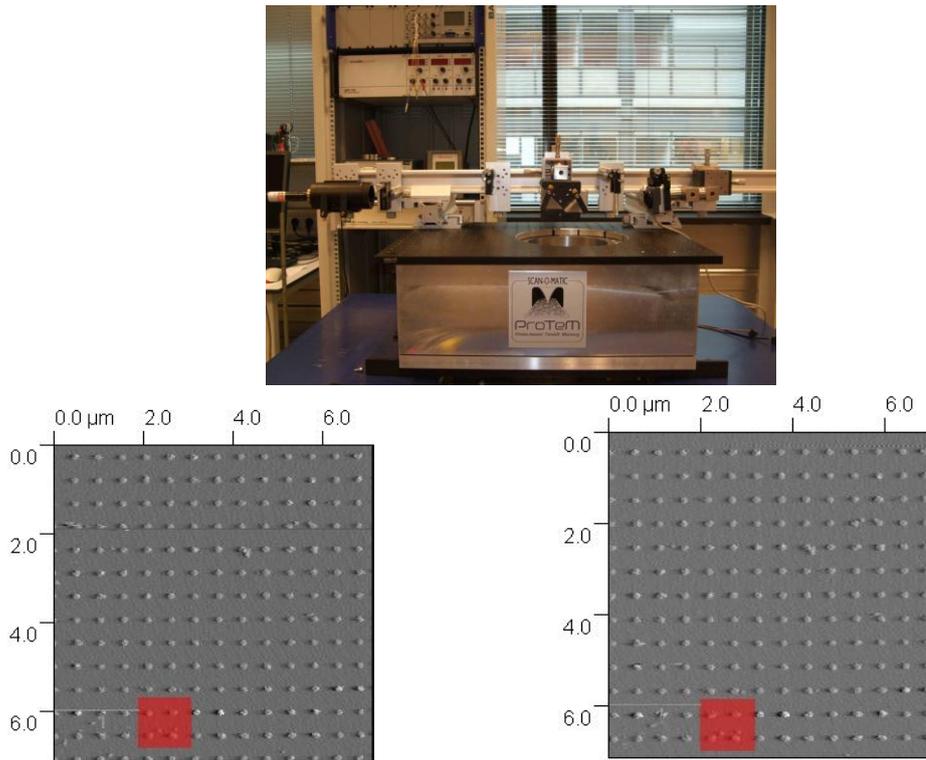


Fig. 3 (top) final realisation of the 'tortoise' system and (bottom) read-back signal before and after a long-range move of several centimeters (red square designates the area that is used to correlate the two scans).

Optical readout

Principal achievements

- The reliability analysis showed that it would be very attractive to move the electronic read-circuitry outside the storage system (a drive concept, such as in tape or optical media). We investigated two methods for optical readout with a single laser beam illuminating the complete cantilever array.
- The first method is based on the fact that individual cantilevers can be identified by their resonance frequency, in the array is designed such that the resonance frequencies are sufficiently different. Small shifts in the resonance frequency can be used to retrieve data. This method was demonstrated on an array with one magnetically coated cantilever. The resonance frequency shift caused by an external magnetic field could clearly be detected, but did not influence non-magnetic cantilevers (Figure 2).
- The second method exploits the effect that the cantilever acts as a diffraction grating. From the diffraction pattern, the relative position of individual cantilevers with respect to the other can be derived. We have shown theoretically that by using clever coding techniques, all data read by each cantilever can be retrieved. Initial experiments have shown that it is indeed possible to discriminate between diffraction patterns.

Applications of research to technology other than probe storage

- Both optical readout techniques are not only applicable to large scale probe storage, but can be used in all situations where cantilevers are used as sensors, such as in gas detectors (artificial noses) or magnetic field sensors.

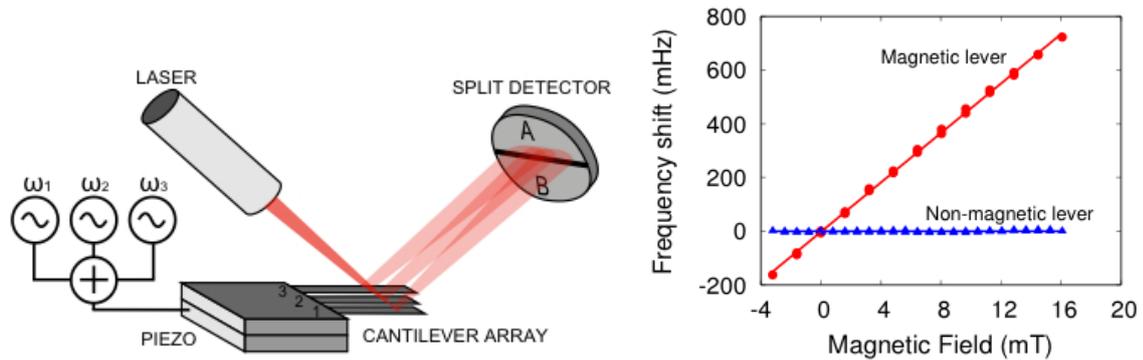


Fig. 4 The resonance frequency shift of a single cantilever in an array can be detected by illuminating the complete array with a single laser beam.

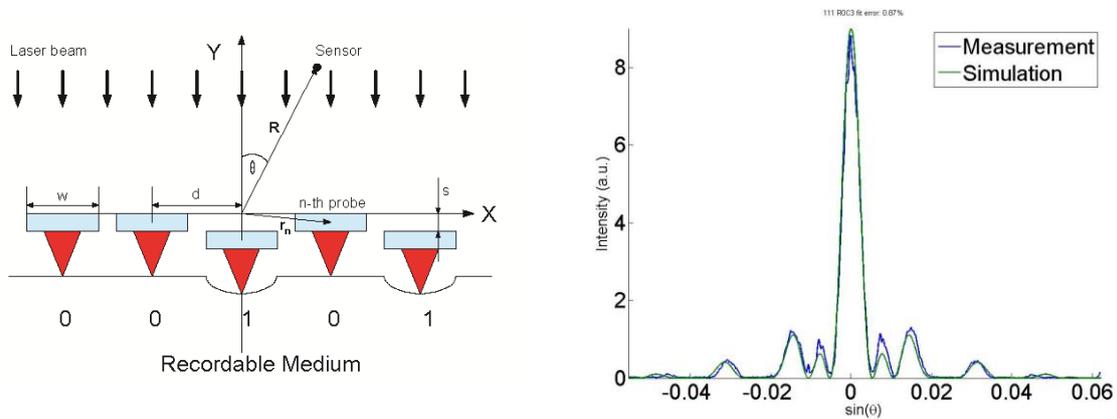


Fig. 5 The remote optical readout system (left) and typical results (right)

WP2 - Nanoscale Write/Read Probe Technologies

Fabrication of a first generation of electrical and thermomechanical probes

Principal achievements

- We fabricated the first generation of thermomechanical probe displaying 10x improvements in power efficiency over previous designs.
- We developed the concept of electrical tip encapsulated in a non-conductive core to mitigate wear (and filed a patent on this).
- We fabricated the first electrical probe with PtSi silicide tip (<10nm radius) encapsulated in a silicon oxide cladding (technology licensing to a European cantilever manufacturer).

Applications of research to technology other than probe storage

- PtSi tip and PtSi tip with silicon oxide cladding has proven to outperform tremendously commercial available conductive probe in term of both wear resistance and current driving capabilities. Such tips are very useful for general conducting AFM technique.
- IBM is also using PtSi tips for investigating phase change material for solid state memory application.
- Moreover, in IBM, PtSi contact is under study for electrical contact for M(N)EMS Switch application.

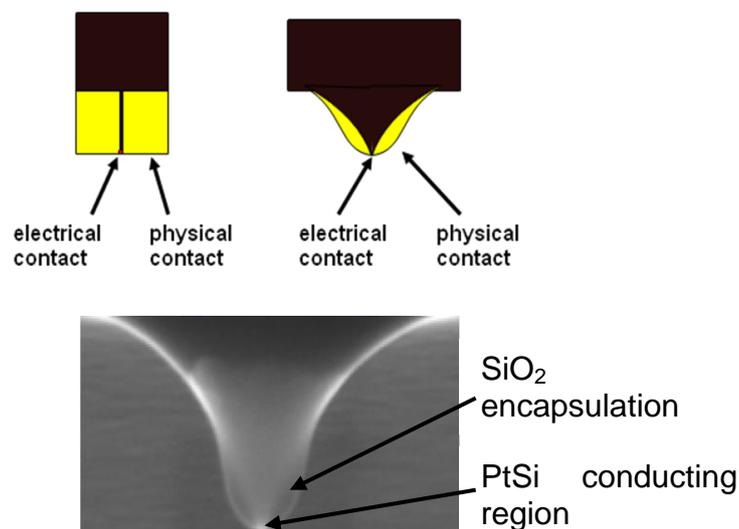


Fig. 6 The PtSi encapsulated tip developed within ProTeM

Definition of probe performance for targeted applications

Principal achievements

- We have concluded that achieving read-speeds of 1MHz with thermomechanical probes could be very challenging. Hence, it has been concluded that we shall find other avenues to offset the lower read-out speed available, such as a larger array to allow for the same data rate.
- For the electrical probes, the challenging aspect is to achieve reliable tip-sample contacts, and we addressed this issue by developing platinum silicide tips

Applications of research to technology other than probe storage

- The result of this study has an impact on designing systems based on probe technology for industrial applications for which the reliability and the throughput requirement are very important. This is the case for metrology, lithography and nanofabrication. In IBM, these results are important for the recent effort on probe lithography using thermo-mechanical lever.

Concept study and simulation on high-performance microprobe structures

Principal achievements

- We designed thermo-mechanical cantilevers with optimized structure for low power operation. For that, a finite element simulation environment based on Ansys was built in which mechanical, electrical, electrostatic and thermal effect has been integrated in the model.
- The simulation tool allows to directly extract readback sensitivity and bandwidth as well as, with the integration of the sensor noise model, the topography resolution limit versus bandwidth.
- Based on the simulation results we developed a new process flow for thermo-mechanical cantilevers which allows fabrication of very thin silicon leads and structural reinforcement with a silicon dioxide strap. Such lever has been use to demonstrate Angstrom-resolution with 20kHz imaging bandwidth at 0.4mW (as predicted by the simulations).

Applications of research to technology other than probe storage

- The simulation environment designed for optimization of thermo-mechanical cantilevers and the knowledge acquired during this work have significantly advanced our level of simulation capability. This is currently used in a number of areas such as
 - cantilever optimization for other applications (metrology and lithography)
 - other research fields including magnetic tape recording, chip and system thermal management, RF MEMS (Nano Electromechanical Switch) for logic application.

- Thermo-mechanical cantilevers are a very powerful tool for metrology and nanofabrication as demonstrated in IBM for contact and dynamic topography imaging, contactless (hovercraft) topography imaging, nanoscale thermal microscopy and, 2D and 3D nanopatterning. We see considerable interest in having access to this technology from researchers around the world.

Technological study on piezoelectric actuation and readout of probes

Principal achievements

- In this task the deposition process for the piezoelectric layers AlN and PZT were developed.
- The AlN sputter process was optimized for high piezoelectric coefficients of thin AlN layers (500 nm) since these thin AlN films offers higher performances on the cantilever structures.
- A suitable patterning process for the AlN film using TMAH and molybdenum as a hard mask and a carrier wafer concept which allows the processing of 4" and 6" wafers on the 8" sputter tool has been identified.
- These processes were combined in a common process platform for IBM and FHG preprocessed wafers for the fabrication of complete piezoelectric cantilevers using AlN piezoelectric structures.
- Although AlN outperforms PZT on the minimum detectable signal level, PZT allows the realization of piezoelectric drives which much higher deflections. *Gas flow* sputtering of PZT offers very high deposition rates but requires high process temperatures to achieve high quality PZT films A *gas flow* sputter process for the preparation of piezoelectric PZT layers was developed and successfully demonstrated..

Applications of research to technology other than probe storage

- The developed technology for the sputter processes of AlN and PZT and the related fabrication processes can be also used for the fabrication other piezoelectric MEMS components. For instance cantilever structures composed of magnetostrictive and piezoelectric layers are suitable for the detection of magnetic fields. These magnetoelastic sensors will enable the realization of highly sensitive magnetic field detectors.

Technological study on tip hardening concept to reduce wear

Principal achievements

- We have developed tip wear reduction method in conduction mode by force modulation techniques. Using our PtSi tip, we have demonstrated that modulation of applied tip-sample load force reduces tip wear volume by a factor three when operating in conductive mode. The major conclusion of this work is that force

modulation, although relying on vertical tip motion, does not prevent proper tip-sample conduction. Instead, modulation effectively enhances the electrical contact between tip and sample. The technique presented can easily be applied to existing conductive probe microscopy setups and effectively increases longevity and reliability of conductive probe applications.

- At IBM, we have demonstrated exceptional wear resistance at the nanoscale of diamond-like carbon. We have developed a process based on molding technique which lead the fabrication of the world's sharpest tips made of diamond-like-material. The outcome of this research done in collaboration with University of Pennsylvania and University of Wisconsin has been published in Nature Nanotechnology which triggered significant press activity.

Applications of research to technology other than probe storage

- Force modulation technique in conducting mode is a new concept which will have impact in AFM metrology. Extending this technique to tapping mode is extremely interesting to study "hot" electrical switching for nanoscale contact with impact outside the scope of probe technology such as Nano ElectroMechanical Switch for logic applications.
- Wear resistance nanoscale structures made of diamond-like materials, such as developed within ProTeM, is of great interest for solving tribology issue in Micro and Nano System. Moreover the method and model use to quantify wear at nanoscale is very generic and its use is not limited to probe technology.

Advanced electrical probe concept

Principal achievements

- We have fabricated cantilever with integrated AlN piezoelectric actuator and PtSi conducting tip for high speed, dynamic mode, scanning probe technology. The integrated actuator allows us to have a reliable excitation of the higher frequency resonant modes, enabling us to take advantage of these modes compared to the commonly used fundamental mode. Hence with the requirement of miniaturization of the cantilever, over 1MHz dynamic mode is possible.

Applications of research to technology other than probe storage

- Our development in integrated actuator to use higher modes dynamic AFM technique for fast imaging is of great interest for application requiring video frame speed. This is useful when dynamic observation of processes is required for example, observing protein motion or crystal growth, or in the industrial measurement market where throughput is an important factor for the choice of metrology technique given its direct impact on cost.
- Other foreseen applications might be in probe nanofabrication, and nanolithography which require much higher speed than conventional AFM techniques to be viable.

WP 3.1 Multi-Terabit per square inch Storage Media: Polymers

WORM media for thermo-mechanical data storage

Principal achievements

- Development of layered media combining mutually exclusive properties of surface toughness, wear resistance, chemical inertness, and thermal stability of highly cross-linked polymers with the soft compliance of uncross-linked polymers in a nano scale composite meta material. The new layered media approach has been combined with the flat media technology yielding unprecedented performance for thermo-mechanical data storage. In particular, we showed that the lifetime target of >50 years at 50°C can be achieved using a stack comprising a 50 nm thick top layer of cross-linked poly-aryl-ether-ketone (PAEK) polymer and a 100 nm thick soft buffer layer of polystyrene.
- Development of a comprehensive media testing protocol allowing fast characterization and comparison of polymer media for data storage.
- Feasibility study of ultra-fast thermo-mechanical writing at a 1 MHz symbol rate. For details see: R.J. Cannara et al., Nanotechnology **19**, 395305 (6pp) (2008).

Applications of research to technology other than probe storage

- The layered media technology is quite generic in its nature and can be readily applied to other fields.

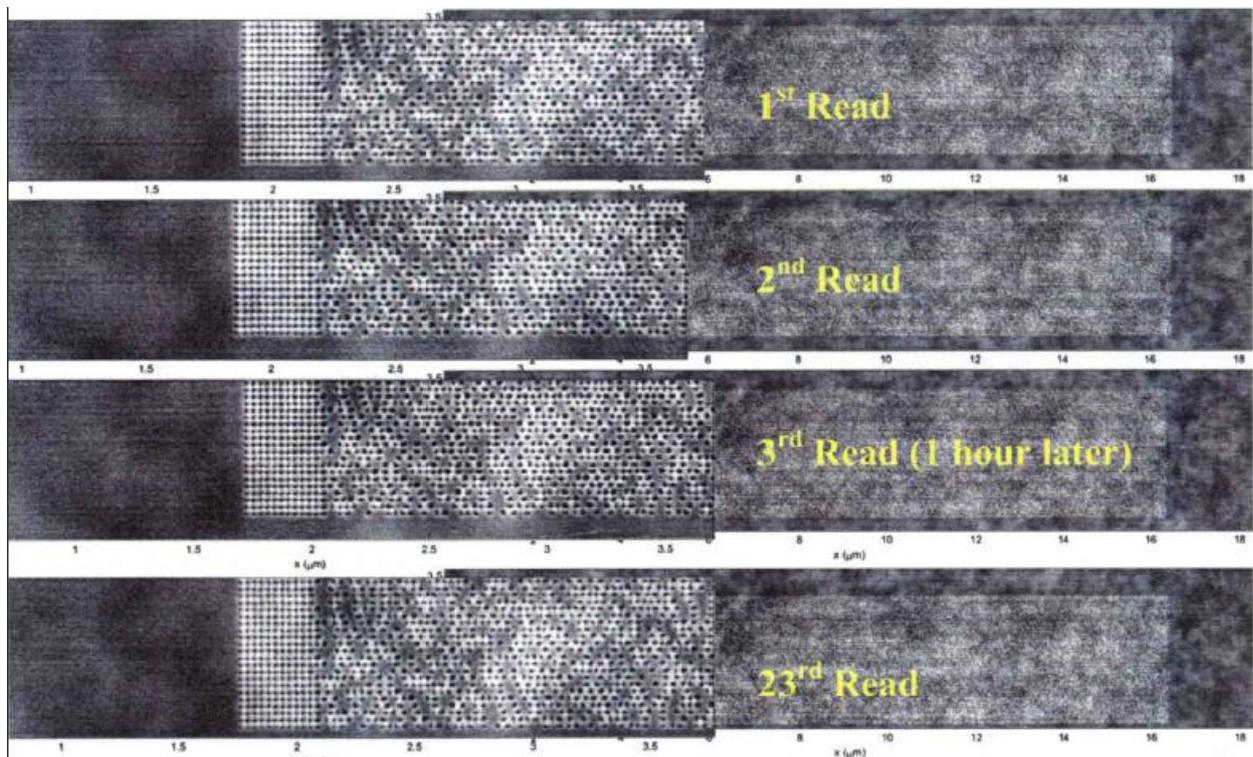


Fig. 7: Large data field of random data written on a PEAK-PS ultra-flat media sample at 1Tb/in² density. The field, measuring 3x15 μm comprises 100 lines of 1000 symbols. Line spacing is 30nm and symbol spacing is 15nm and the data is encoded using d,k code of (1,7). Note that no degradation of the bit pattern can be seen after many read repetitions.

Development of fabrication techniques for ultra-flat polymer films

Principal achievements

- Development of a replication technique for achieving ultra-flat polymer surfaces with a mean roughness of less than 0.1 nm. Thus, shallow indents with a depth of less than 2 nm can be reliably detected, which forms the basis for achieving high storage densities.
- The ultra-flat media technology has been used in a 6 Tb/in² storage density demonstration
- Full characterization of the roughness spectrum of standard and ultra-flat media: The surface roughness of standard media is characterized by a 1/q² power spectral density due to thermally excited capillary waves giving rise to a self-affine fractal structure with a Hurst exponent H=3. The structure of the ultra-flat surface, featuring substantially less corrugation, is qualitatively different by exhibiting a 1/q power spectral density which is characteristic for bulk elastic waves. (Pires et al., “Ultraflat Templated Polymer Surfaces”, *Langmuir* **25**, 5141-5145 (2009))

Applications of research to technology other than probe storage

- The ultra-flat media technology solves one of the generic problems in polymer surface technology. The surface roughness is known to be crucial for wear resistance, low friction, adhesion properties, polymer- bio-mass interaction, to mention just a few. One may expect that the technology will find applications in other fields not related to data storage.

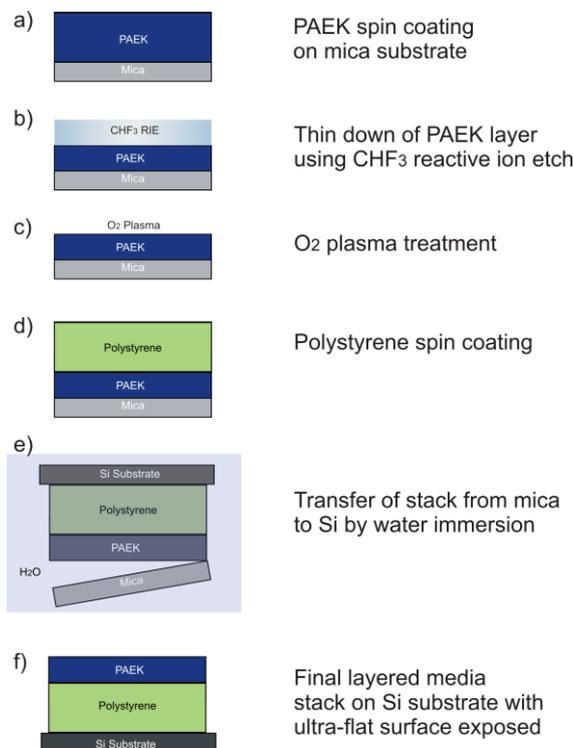


Fig. 8 Schematic process flow used for the fabrication of ultra-flat layered PAEK media

Plasma deposited polymer films for thermo-mechanical data storage & layered media using plasma deposited norbonene as top layer

Principal achievements

- Development of an alternative technique for the fabrication of layered media. Here, a highly cross-linked top layer is plasma deposited on the soft underlay. The technique is particularly well suited for large scale production.
- Fabrication of SiO₂-rich (HMDSO) hydrophilic and pure hydrocarbon containing (norbonene) hydrophobic top layers with nm thickness on polystyrene underlayers featuring exceptional wear resistance and overall indentation compliance comparable to the bulk properties the respective materials.
- Demonstration of high density (1.8 Tb/in²) data recording and virtually perfect single pass erasure using writing forces of less than 100 nN on a norbonene-polystyrene sample.

Applications of research to technology other than probe storage

- The plasma deposition process can be used in a generic sense for fabricating nano scale layered meta materials. One can easily conceive multi layer structures, an option that hasn't been explored at all within the frame work of ProTeM.

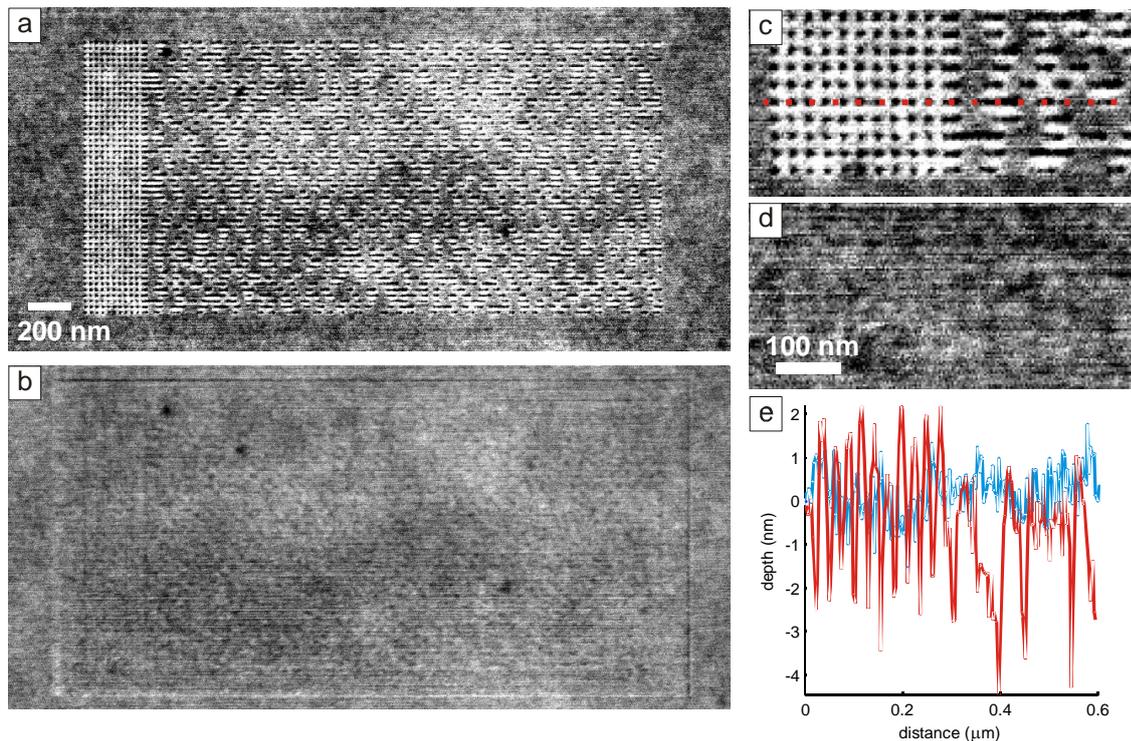


Fig. 9 Thermomechanical writing and erasing of bit patterns. a) and c) bit field written in the layered media with the thinnest ppNb layer of 6 nm. The heater temperature and force for writing were 350°C and 80 nN, respectively. A pulse duration of 10 μs for the force pulse and the heat pulse were used. b) and d) shows the same area as a) and c) after performing an erase operation. The groove pattern is cleanly removed and only some defects of the polymer film are visible. e) cross-sectional profiles along the line of grooves as depicted by the red dotted line in panel c). The depth of the grooves is between 2 and 4 nm (red line), whereas the erased surface (blue line) has a roughness of ~ 2 nm peak to peak, similar to the roughness of a virgin surface.

Development of petrified information (guaranteed write once, ultra long bit retention) media

Principal achievements

- Development of a true write once probe storage technique based on the local evaporation of a phenolic molecular glass resist. The technique is ideally suited for groove recording and data recording at 1.5 Tb/in² storage density has been demonstrated.
- Demonstration of multi-level recording using a phthalaldehyde polymer resist for patterning and subsequent “petrification” of the data pattern in SiO₂ by means of reactive ion etching. Thereby, the information is preserved in a material with retention properties and thermal stability far exceeding those of any known storage technology.
- Petrified data storage is very much at a conceptual stage and it is not clear to what extent the market would be willing to accept such a radical approach. From a scientific and technological perspective, a broad range of topics need to be studied, including the optimum design of the template resist, optimization of the pattern transfer, exploration of the density limits, and system design aspects.

Applications of research to technology other than probe storage

- Tip induced evaporation of polymer resists is a generic high resolution patterning technology that can be used for a broad range of lithographic applications, including classical 2-dimensional patterning but also extending the capability to the third dimension as demonstrated in this task. This novel direct write technique offers a number of unique attributes, such as in-situ inspection and metrology, fast patterning rates, high resolution of better than 20 nm and absence of long range proximity effects, easy control of the patterning depth for 3-dimensional patterning, overall low equipment complexity and cost, compatibility with standard processing used in the micro-electronics industry, which give it a strong standing in comparison to traditional e-beam techniques.

Ultra-fast thermomechanical writing and non-invasive reading schemes for polymer media

Principal achievements

- Development of the so-called dither (or force modulation) technique to mitigate media wear problems encountered in contact imaging of polymeric materials and soft matter in general. For details see: A. Knoll et al., “Wear-less floating contact imaging of polymer surfaces”, *Nanotechnology* **21**, 185701 (8pp) (2010).
- Design and construction of a probe patterning system featuring 50 μm linear scan range in x and y, up to 24 mm/s scan speed in the x-axis, 10 nm position accuracy over the whole scan range at 10 mm/s scan speed, and 20 mm coarse positioning in x and y.
- Demonstration of 100 k lines/s read back bandwidth using thermo-electric height sensing.

- Demonstration of high precision error free patterning of a fractal carpet structure comprising 880 x 880 pixels at a sustained writing rate of 2 μ s per pixel, a pixel position error of no more than 10 nm over a scan field of 13 μ m x 13 μ m, and a minimum size of the written features of 30 nm.

Applications of research to technology other than probe storage

- We have taken probe patterning in general to the next level by demonstrating an overall system performance which is on par with high resolution e-beam writing. The work forms the basis for a new probe based lithography which could become an important tool for rapid prototyping, mask fabrication, and eventually low volume production - see *Ph.C. Paul, A.W. Knoll, F. Holzner, M. Despont, and U. Duerig, "Rapid turnaround scanning probe nano-lithography", Nanotechnology (accepted for publication).*

WP 3.2 Multi-Terabit per square inch Storage Media: Phase-Change

WORM media

Principal achievements

- Crystalline bits writing with pulse length down to 350ns (rise of fall times of 100ns)
- Demonstration of electrical switching of TePdO, a material initially developed for optical archival data storage.
- First precise measurement of the recrystallization speed of the phase-change materials $\text{Ge}_2\text{Sb}_2\text{Te}_5$ and $\text{Ge}_8\text{Sb}_2\text{Te}_{11}$ as a function of temperature.
- Enhanced bit retention stability when the media is initially in its amorphous state compared to the crystalline case.
- Significant development of WO phase change based stacks including much reduced roughness (only 0.1nm larger than the substrate roughness) which should allow increased bit writing density
- A standardised four layer WO phase change stack was defined (materials, conditions, thicknesses) and evolved through three iterations (design centers).
- GST8211 was shown to have higher crystallisation temperature, but otherwise similar IV characteristics. A lower nucleation rate means that marks < 20nm diameter cannot be made reliably.
- Sputtered carbon shown to be a strong candidate as an alternative to phase change for WO memory which may also be used in solid state memory

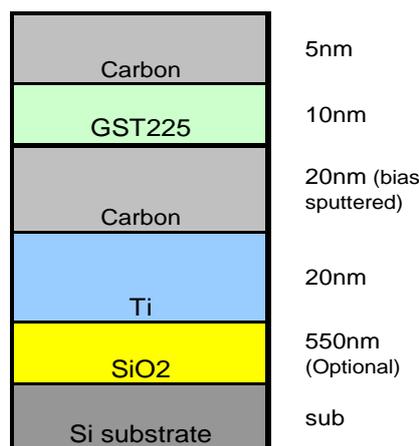


Fig. 10 The Design Center 4 WORM phase change stack which should have a low roughness (for high data density) and a better lifetime due to slower degradation of the capping layer.

Re-Writeable Media

Principal achievements

- Design, building and test of a new setup (POET), which enables the in-situ investigation of crystallization kinetics with a time-resolution of 0.5ns. One of its key features is the ability to study time-resolved phase transitions as a function of temperature. The software and many hardware components of the POET set-up are also employed in a purely electrical tester, which will soon be commercialized.
- Determination of growth velocity of GeTe₆ and AgInTe₂ phase-change materials thanks to the POET setup.
- Significant progress in understanding the charge transport in amorphous and crystalline phase change materials, which has produced remarkable scientific insights. This should help in developing advanced storage strategies (patent application filed).
- Use of the POET setup to investigate crystallization kinetics of many more phase-change materials, especially fast growth materials.
- Setting of a C-AFM system suitable for writing arrays with pulse width down to 100ns.
- Optimization of amorphous bit recording through numerical modelling
- Amorphous bit writing with 35nm pitch on GST/carbon media.
- Carbon capping layer writing identified as major constraint for amorphous bit recording
- Development of carbon films as potential new WORM media

Applications of research to technology other than probe storage

- C-AFM pulsed setup to test electrical memories/switching properties at nanoscale (phase-change memory materials, resistive memory materials).
- Possibility to fabricate patterned conductive templates for local selected electro-deposition, using C-AFM setup

Media tests

Principal achievements

- Extensive characterization of carbon thin films properties (resistivity, roughness, structure, wear) as a function of deposition conditions
- Isochronal lifetests up to 105C for 100 hours on GST225 based media that still give readable marks (low density data)

- Many materials tested and excluded from further work such as TePdO, ZnS-SiO₂:SbSnIn, Cu:Si
- Alternative capping layers ruled out include CrSiO₂ and alternative conductive underlayers ruled out include Mo
- Development of phase change based stack with good lifetime, good wear (read) properties and very low roughness to allow high data densities.

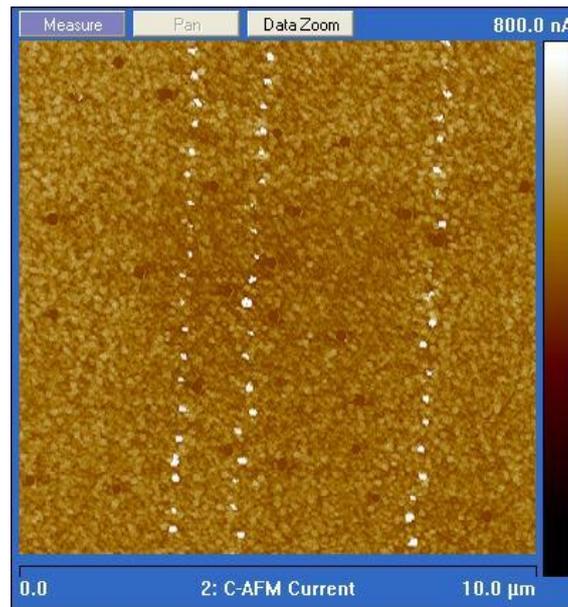


Fig. 11 A conductive image of written marks on a WO phase change stack after lifetesting at 95C for 100 hours.

Additional morphological and physical characterization

Principal achievements

- TEM cross section of GST amorphous media with crystalline marks showing full thickness crystallization and carbon layer damage.
- Measurement of thermal conductivity of carbon thin films.
- Carbon thin films thermal stability characterization: quantification of resistivity evolution and structure after annealing as a function of thickness and deposition conditions.

Applications of research to technology other than probe storage

- The ability to perform cross-sectional TEM on the nanometric scale is applicable to a wide range of technological and scientific fields

WP4 - Multi-Terabit per square inch Recording Technologies:

Test-stand building and modifications

Principal achievements

- Building of specialized AFM testing setups with high flexibility for different cantilever designs; universal cantilever-tip holder, 3D piezoelectric scanners/controllers, data-acquisition system, custom-made analog front-end PCB.
- A powerful data acquisition system; high-speed ADC/DAC boards, programmable FSMs, fast DSP, Matlab interface to the PC. Environment is programmable to accommodate various probe designs and recording techniques
- Fast scan technology with conventional piezo scanning stages; custom-made charge amplifiers were built for the fast scan axis, that reduce hysteresis and improve the dynamic behavior of the scanner. Custom made digital controllers were built. Scan frequencies up to 100 Hz achieved.
- Development of dedicated Labview programs with specific graphical interfaces to implement additional capabilities into the initial AFM test stand:
- I(V) capability: it consists in measuring the current flowing through the media as a function of the applied voltage. Most of the AFM's softwares and hardwares are offering the I(V) purpose but on a steady mode only. In the PROTEM setup, a 2D cartography of the I(V) characteristics is acquired at a common scanning rate (typically 5Hz), by using a high speed voltage acquisition and generation board: it allows to evaluate the existence of the electrical switching process of the considered materials as well as the homogeneity of the threshold voltage.
- Acquisition of the current levels involved during writing (it includes the current passing through the sample before, during and after the writing pulse): it allows the analysis of stability and reliability of the recording process and complements the information given by the conduction images.

Applications of research to technology other than probe storage

- The additional capabilities that have been set up are useful tools to characterize the local electrical properties of nanostructures. In particular, still in the data storage technology, such tool is used to evaluate the I(V) characteristics of PCRAM devices, based on a patterned media. It has been also considered to investigate the electrical behaviour of ZnO nanowires for solid state lighting applications. Automatic bench tests are usually available to characterize such devices, but they operate on full wafers (200mm or 300mm) and require the fabrication process to be complete. With a conductive probe-based test stand, it is possible, relatively easily, to probe each individual PC bits (in PCRAM devices) or each nanowires (in the case of lighting applications) on simplified structures and smaller samples than real devices, limiting the technological steps and consequently the involved cost.

- The powerful and flexible test-stands developed under ProTeM are also currently being used for the investigation of new phase-change materials for phase-change memory through interrogation with conductive AFM probes.

Software development for readback signal processing

Principal achievements

- Matlab-based comprehensive software platform for the analysis of captured readback waveforms;
- Information such as signal and noise amplitude and frequency spectra, signal-to-noise (SNR) and signal-to-distortion (SDR) ratios, noise/distortion power, and medium surface roughness, jitter measurements, and linear/nonlinear channel identification is provided.
- Phase-change media: Recording of well defined crystalline bits matrices with writing times down to 350ns, under moderated voltages ($< 5V$), that have shown high readout contrasts (of several orders of magnitude).

Key research topics that still need to be addressed

- Phase-change media: The recording tests that have been performed all along the project on various media (differing by the materials used and their structures) have pointed out that reliability of the tip/media contact and tip wear during the writing process are still an issue. The numerous variations of media investigated and of tips used made the analysis relatively complicated, as the influence of each parameter was difficult to distinguish from the experimental data.
- The implementation of force modulation in conductive AFM has shown promising results in reducing wear and in the establishment of the tip/media contact while scanning a uniform surface of PC media. The potential of force modulation configuration in real recording mode (i.e. during writing and reading processes of bits matrices) on phase-change media would be an important aspect that still needs to be addressed.

Applications of research to technology other than probe storage

- The software suite developed, with appropriate modifications, is currently also being used for the AFM-based investigation of new phase-change materials in phase-change memory applications.

Recording tests

Principal achievements

- Definition of a media wear test (number of read passes) protocol

- Able to make up to 500 read passes on phase change media using low Ra stacks, low k (0.3 N/m) PtSi tips in force modulation mode. The number of reads was limited by the test time to one day of reading, so 10^3 to 10^4 read passes should easily be possible

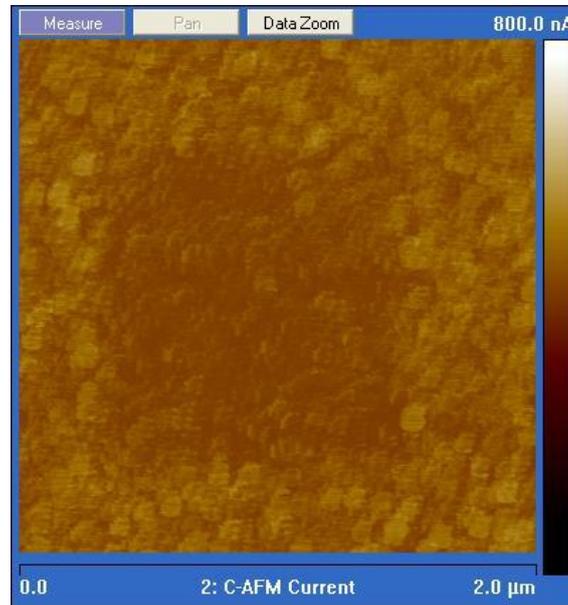


Fig. 12 A conductive image of WORM phase change stack after 500 wear or read passes of a PtSi tip in the central (1 μ m x 1 μ m) region

- New scheme for readback of topographical indentations, based on intermittent-contact between tip and medium. Main advantage is large reduction of tip and medium wear by avoidance of lateral and shear forces that damage tip and medium in contact mode of operation. Continuous reading of a once-written medium portion was achieved thousands of times, with total equivalent tip travel distance of 140m. Tip sharpness at the end of the endurance experiment is adequate to record and reliably read data at 1Tb/in². This is the first time that such high tip/medium endurance has been shown, by continuously maintaining high reliability in the read back data.
- Novel scheme for data recording in polymer media, named “Groove Recording”. Information is carried by the length of grooves/lands formed on the medium, as opposed to the presence/absence of marks. Ultra-high storage density of approximately **8 Tbits/in² has been achieved**. Scheme was also applied to phase-change media with initial success.

Applications of research to technology other than probe storage

- Intermittent-contact (i.e. force modulation) interrogation of samples is a very powerful technique with high potential for the imaging of soft, delicate samples with the AFM, e.g. biological tissue.
- The principle of groove recording has also been used for the creation of nanoscale structures in specially designed polymers, which are then used as transfer masks for definition of high-aspect-ratio nanoscale objects. The main application is semiconductor lithography beyond the current photo-lithographic limits.

Write/read/erase modelling, noise modelling and performance assessment

Principal achievements

- Accurate models for signal and distortion for thermo-mechanical recording; performance evaluation of thermo-mechanical recording through analytical and simulation results.
- System-level analysis of reliability of massively parallel probe storage device and determination of ECC requirements for reliable probe storage
- Characterisation of thermo-mechanical probe storage channel
- Low complexity probe-by-probe sequence detection hardware algorithms
- Low complexity detection hardware algorithm for large arrays of probes affected by positioning errors
- Minimal requirements for ECC scheme to deal with global positioning errors
- Hardware algorithms for optical readout technique for probe storage which allow to separate probe array from electronics
- Experimental validation of groove-based thermo-mechanical recording at **information density 6 Tb/in²** with pre-ECC bit error rate of 3×10^{-4} and at an **information density approaching 8 Tb/in²** for a slightly worse (but still usable with modern ECC) error rate of 7×10^{-3} .
- Physically realistic and accurate models for write, read and erase processes in phase-change probe storage.
- Identification of potentially viable RW scheme using slow-growth phase-change materials
- Demonstration, experimentally and theoretically, of a mark-length write scheme (groove-recording equivalent) for phase-change recording with the potential to increase densities by 50% to 100% over conventional recording approach

Applications of research to technology other than probe storage

- Application of detection algorithms and channel performance bounds derived for global positioning errors to deal to storage channels with correlated error events (HDD's - off track errors, thermal asperity; SSD's - uneven block wear; Optical storage: long scratches on the storage medium)
- Use optical readout techniques for parallel AFM. Applications: material engineering, biology
- Application of phase-change modelling to PCRAM device design and the development of new phase-change based technologies (e.g. phase-change memristors, phase-change processors)

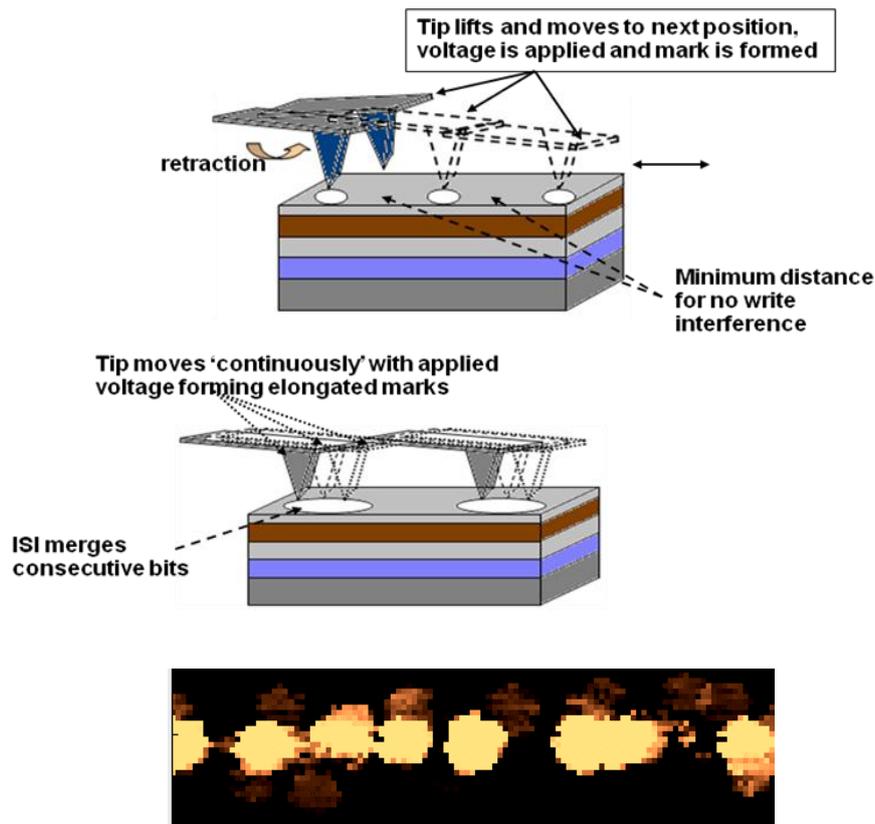


Fig. 13 Schematic (top) of conventional mark-position recording, as used in probe memories to date; schematic (middle) of a new mark-length recording strategy and (bottom) a current image of mark-length recorded bits in a phase-change medium (image is 580 nm x 140 nm and recorded bit sequence is 11001110111101110001111000111 with a bit cell length of 20 nm)

File system investigation for Probe Storage

Principal achievements

- Designed a storage system hierarchy and associating reduction method. The reduction method supports important reductions of system compositions such as k-out-of-n composition using identical units, series and parallel compositions, and standby redundancy. For the latter we derived a close expression that can be used in the presented reduction methods.

Key research topics that still need to be addressed

- Redundancy opportunities have been captured in parameters of the design space through parameters, e.g., k-out-of-n, and hierarchy. A thorough validation of the framework and exhaustive experimentation with the framework remains to be done.

Applications of research to technology other than probe storage

- Redundant file systems are of interest to all critical storage systems. The file system developed in ProTeM does not restrict itself to probe storage.

Summary

In summary ProTeM has been an enormously successful Integrated Project that has advanced the state-of-the-art in probe-based storage systems and related areas of nanotechnology and materials science. ProTeM has ensured that Europe remains at the forefront of scanning probe based technology and is well-placed to exploit any future opportunities in this scientifically and technologically important area. The major successes of the project are highlighted succinctly in Figure 16 below - taken from presentations made at the final review of the project held in Brussels in January 2011.

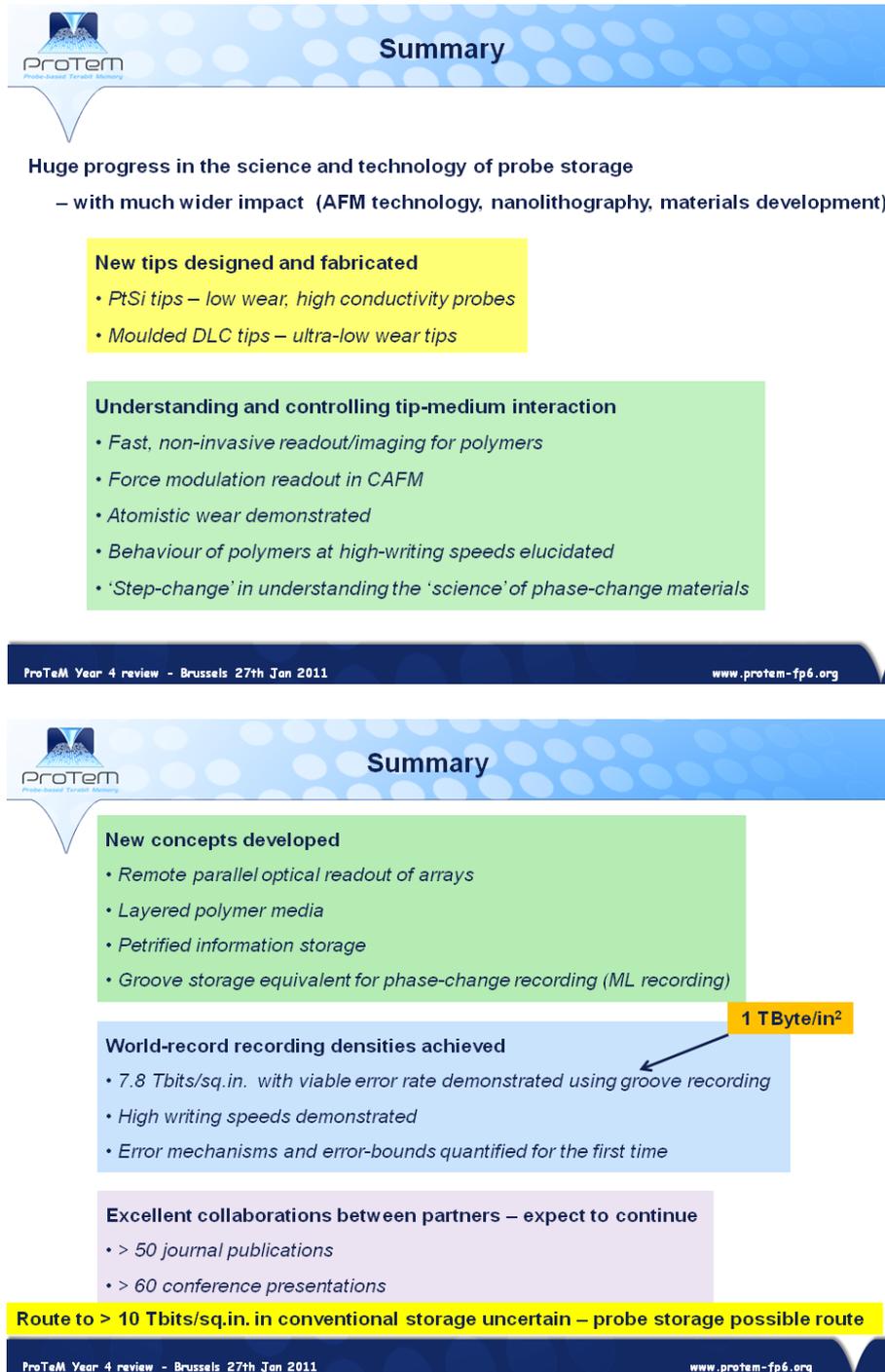


Fig. 14 Summary of main ProTeM achievements