Part I

U-H-D Recording Media

Materials Challenges for Tb/in^2 Magnetic Recording

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Summary. Magnetic recording technology aims to provide the capability of storing as much as 10^{12} bits/in^2 (1.6×10^{11} bits/cm^2) in the foreseeable future. This remarkable storage density projection is made possible by recent major improvements in the microstructural and intrinsic magnetic properties of the thin film materials utilized for both recording and reading nanoscale magnetic domains which form the basis for digitally encoding information. To meet the Tb/in^2 goal, further reductions in the recording medium grain size, the grain size distribution as well as increments in the magnitude of the magnetic anisotropy will be required. Currently used longitudinal recording materials are unlikely to support such high density targets and a migration to perpendicular recording is expected. On account of the superparamagnetic limit and the need for stringent control on the domain size, it is also likely that a transition to patterned media will also be required. The read sensor sensitivity will also need to increment to provide large enough signals needed for low error rate. Therefore, breakthroughs in magnetic thin films for the disk and head components will be required to meet the technology goals.

1 Introduction

The key elements of a hard disk drive are: the recording medium, the write and read head elements, the mechanical actuator, the signal processing devices and the ancillary electronic components to record, read and to perform reliable seeking operations. Magnetic thin films play a key role in enabling this technology. They constitute the storage medium and are the key elements of the write and read head elements. Data is recorded by locally altering the direction of the magnetization in the recording medium via the magnetic field generated when current is passed through the lithographically defined coils within the recording head structure. The bit size is determined by the geometry of such write head. Data is read and processed by sensing the out-of-plane magnetic flux arising at the boundaries between recorded bits. These small magnetic fluxes are detected by utilizing thin film read heads that exploit the magneto-resistive effect when subjected to a magnetic excitation. Today's read heads which are mainly spin valves employ sensor materials exhibiting giant magnetoresistance.

To increase the storage density, the magnetic bit size and the inter-bit separation along and across data tracks must be reduced. This scaling approach has worked out very well with only minor changes in the structural and magnetic properties of the recording layers up to storage densities around 1 Gb/in^2 . Significant improvements in reducing the grain size and the intergranular exchange coupling have permitted the extension of longitudinal recording alloys up to storage densities around 100 Gb/in^2. To circumvent losses in flux amplitude that are inherent to the 1000-fold reduction of the bit size, higher sensitivity sensor materials have been developed and the physical spacing between the topmost layers of the recording of the medium and the read sensor has been reduced from $\sim$ 100 nm to $\sim$ 10 nm. Flying reliably at such small distances imposes stringent demands on the thickness and smoothness of the recording thin film structures. In particular, the overcoat (typically amorphous carbon) thickness must be reduced to a minimum ($<$ 5 nm) while preserving its mechanical integrity and strength to provide not only environmental protection to the recording layers, but also mechanical robustness. It is obvious from these overall considerations on magnetic recording technology, that the microstructural control at the nanoscale level of the multiplicity of layers that comprise the recording medium as well as the elements of the read and write head, will play a critical role in extending the technology to and beyond Tb/in^2.

The workshop addressed many facets on fundamental magnetism and materials growth and characterization that are critical to sustaining the viability of magnetic recording technology into the XXIst century.

2 Materials Challenges

The microstructural and magnetic properties of the thin films employed in magnetic storage technology will determine to a large extent the attainable density recording limits for magnetic recording. Consider first, magnetic thin films for storing the magnetic information. Increasing linear density requires that the domain wall between recorded transitions be decreased. Recording at 1.0 Tb/in^2 will require bit dimensions of $\sim$ 15 nm in diameter (for cylindrical bits) and a bit spacing of $\sim$ 10 nm. It is highly unlikely that current granular media which consists of magnetic grains segregated by a secondary non-magnetic phase will meet these requirements. The smallest magnetic grain diameter attainable with present sputter deposition fabrication methods is of the order of 5 to 7 nm. In addition, the grain size distribution of said recording materials is inadequate for meeting the stringent requirements for recording at the Tb/in^2 regime. Therefore a migration to fabrication methods or growth techniques that provide a regular array of magnetic nanoparticles is of paramount importance. Utilizing lithographic techniques and current thin film growth technologies is a viable approach. Nevertheless, it should be recognized that the minimum feature sizes needed, as well as the spatial distribution tolerances for Tb/in^2 are so stringent that current lithographic techniques will not satisfy said requirements and tolerance limits. Breakthroughs in lithography will be needed to meet the aforementioned density goals. Self-assembly of nanoparticle arrays provides another approach for generating the desired characteristics of the recording medium. Significant improvements in this area are discussed in these proceedings. Some of the challenges for self-assembly growth methods to be of practical use for magnetic recording technology pertain to the need to provide large areas of self-assembled particles exhibiting the spatial distribution that have been achieved over small areas, as well as the need to develop long range magnetic order of the nanoparticle assembly.

It is important to realize that the island size and thus, the magnetic volume cannot be arbitrarily reduced. This is on account of the superparamagnetic effect. When a single isolated magnetic particle reaches a minimum critical volume, the magnetocrystalline anisotropy is no longer sufficient to overcome the thermal energy that tends to randomize the magnetic axis orientation. This limit indicates that isolated spherical Co particle of 7.6 nm in diameter become superparamagnetic at room temperature. The limit for a given ferromagnetic material, is determined by the magnitude of its magnetic anisotropy energy. Therefore, future recording thin films will need to employ higher anisotropy materials than current Co-based alloys. A fertile area of investigation is the permanent magnet field in which anisotropies exceeding 10 to 200 times that of current recording materials have been reported. Similarly, ordered alloys such as FePt could in principle provide stable islands down to $\sim$ 3 nm in diameter. A critical caveat in the practical utilization of said high anisotropy materials is their writability. Because of their high intrinsic anisotropy, the writing coercivity of said materials is too high to permit current write head devices to control their magnetization direction. It will become either necessary to employ some form of thermomagnetic recording to reverse the magnetization direction. Applying a heat pulse during the write operation, permits a drastic reduction in coercivity, thereby allowing current write head devices to be used concurrently with the heat pulse. Alternatively, nanoscale spring magnet materials could in principle be employed. Said materials comprise two ferromagnetic structures which are strongly exchanged coupled. One component is magnetically soft and the other is magnetically hard. The soft material easily responds to the external field and through a magnetic torque effect is able to drag the magnetization of the hard magnet component.

In the area of the read sensor, significant advances will also be required for Tb/in^2 applications. The GMR response needs to be driven to higher values to compensate for losses in magnetic flux as the domain size is reduced. Novel spin-valve geometries including CIP need to be explored to extend GMR coefficients. Additional impetus for the development of higher sensitivity sensor materials has been injected by recent developments in magnetic tunnel junction devices and other spintronic materials and devices. However, as the feature sizes in read sensor materials are continuously decreased, thermal fluctuations of the magnetic order in said magnetic materials will play a key role in limiting their extendibility to ultra-high density recording. Said fluctuations labeled as magnetic-noise could become dominant in some magnetic read sensor devices with further scaling reductions.

Thus, the future evolution of magnetic storage technology critically depends on major advances in thin films physics, materials development and fabrication engineering. The proceedings of this workshop provide a wide range of contributions that seek to provide fundamental understanding and address solutions to such critical materials challenges.

Scanning Hall Probe Microscopy: Quantitative & Non-Invasive Imaging and Magnetometry of Magnetic Materials at 50 nm Scale

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Summary. Scanning Hall probe microscopes have proven themselves to be quantitative and non-invasive tools for investigating magnetic samples down to 50 nm scale. They can be run in a wide range of temperatures and have unprecedented field resolution which is not affected by external fields. Local magnetometry of very small volumes is also feasible opening up very promising avenues for characterization of magnetic nanostructures.

1 Introduction

Scanning Hall Probe Microscopy (SHPM) [1, 2] is a quantitative and non-invasive technique for imaging localized surface magnetic field distribution on sample surfaces with high spatial and magnetic field resolution of $\sim$ 50 nm & 70 mG/$\sqrt{\text{Hz}}$, over a wide range of temperatures, 30 mK–300 K. This new technique offers great advantages and complements the other magnetic imaging methods like Magnetic Force Microscopy (MFM) [3], Magnetic Near Field Scanning Optical Microscopy [4] and Kerr Microscopy [5]. In SHPM, a nano-Hall probe is scanned over the sample surface to measure the perpendicular component of the surface magnetic fields using conventional Scanning Tunneling Microscopy (STM) positioning techniques as shown in Fig. 1. The SHPM system can be designed to enable operation over a wide temperature range, (30 mK–300 K). The SHPM has started as an obscure SPM method with very limited performance and applications at cryogenic temperatures, to a well-fledged magnetic characterization technique with 50 nm spatial resolution and extremely high field resolution. The first microscope [1] could get an image over many hours at 4 K due to noise; in contrast to 1 frame/s scan speeds of modern SHPMs, even at room temperature. The state of the art SHPMs' field resolution is now capable of imaging magnetic vortices in room temperature superconductors, if one day, someone discovers them. SHPM is a quantitative and non-invasive method, compared to MFM with similar spatial resolution. The nano-Hall sensor's used in the SHPMs do not saturate under high external fields and the technique has been shown to operate up to 16 T. The microscope can also be used as a local scanning magnetometer with extremely high magnetic moment sensitivity and can measure magnetization loops of individual magnetic nanodots. SHPMs have recently been commercialised for low and room temperature applications [6]. The performance of the SHPMs can be improved further down to 10–20 nm spatial resolution, ps time resolution, 6–8 frames/s scan speeds, without sacrificing the field resolution drastically.

2 Experiment

2.1 Scanning Hall Probe Microscope

The RT-SHPM [6] used in our studies has a scan range of 56 × 56 µm in XY directions and 4.8 µm in Z direction. The SHPM incorporates XYZ motors for coarse micro-positioning, a video camera for Hall sensor alignment, another video microscope integrated into the piezo scanner with ×14 optical magnification for visualization of the sample and an integrated coil concentric to the Hall sensor head for the application of external magnetic fields of up to ±40 Oe. Furthermore, a newly developed compact sized powerful pulse coil can be coupled with the system to apply external fields up to ±25,000 Oe. The Hall sensor is positioned close to a gold-coated corner of a deep etch mesa, which serves as STM tip. The Hall probe chip is tilted $\sim 1^\circ$ with respect to sample ensuring that the corner of the mesa is the highest point. The microscope can be run in two modes: STM tracking and lift-off mode. In the STM tracking mode, the tunnel current between the corner of the Hall sensor chip and the sample is measured and used to drive the feedback loop enabling the simultaneous measurement of both STM topography and the magnetic field distribution of the sample surface. This mode of operation gives the highest sensitivity because of the smallest probe-sample separation at all times, but with the drawback of being slow. In the lift-off mode, the Hall sensor is lifted off to a certain height above the sample and the head can be scanned extremely fast ($\sim$ 4 s/frame) for measurements of the local magnetic field distribution. AFM tracking SHPM has recently been developed, integrating a micro-Hall sensor onto a SiN AFM cantilever [7] and onto a GaAs AFM cantilever with sharp tip [8]. The force is measured and controlled by optical [7] or piezoresistive [8] detection.

The LT-SHPM [6] used in this study is very compact (23.6 mm OD) and has the same features of RT-SHPM. It can operate between 30 mK–300 K and tested up to 16 T external fields. The sample can be positioned within 3 mm in XY directions.

The minimum detectable magnetic field is limited mainly by the noise of the Hall sensor, dominated by Johnson and 1/f noise. Nano-Hall sensors are driven with a DC current, (I_{HALL}) and the Hall voltage measured using a low noise amplifier positioned close to the nano-Hall probe. The amplifier's gain and bandwidth are adjustable parameters. The minimum detectable magnetic field with a Hall probe can be written as [2],

$$B_{min} = V_{noise}/(R_H I_{HALL}) \qquad (1)$$

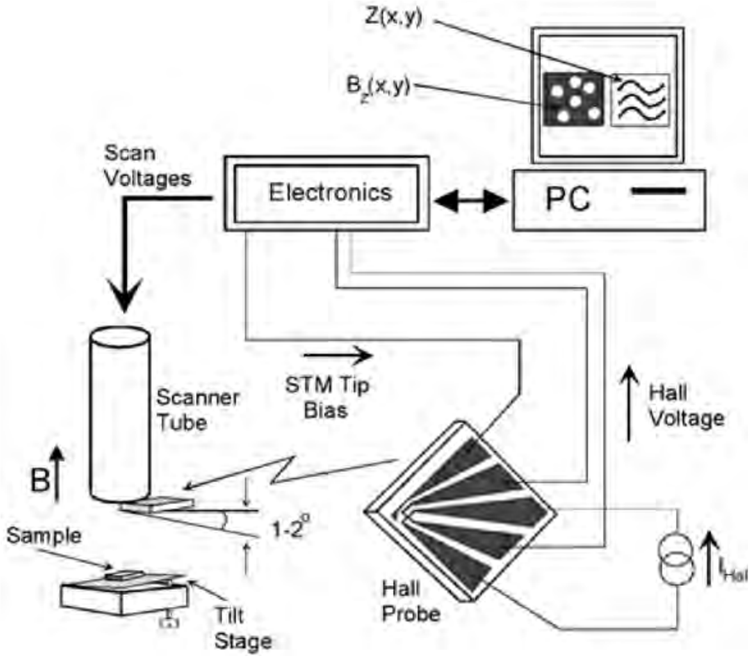

Fig. 1. Schematic diagram of Room Temperature Scanning Hall Probe Microscope (RT-SHPM).

where V_{noise} is the total voltage noise at the input of the Hall amplifier. The voltage noise of the amplifier can usually be made negligible. The V_{noise} has two components; and the Johnson noise due to the series resistance of the Hall sensor (R_s) and the 1/f noise. It is desirable to drive the Hall probe with the highest permissible current. However, the voltage noise of series resistance R_s increases due to heating of the charge carriers and the lattice. Therefore, the Hall current cannot be increased indefinitely and there is a maximum useable $I_{HALLmax}$.

2.2 Hall Probe Fabrication

We earlier exploited excellent properties of GaAs/GaAlAs two Dimensional Electron Gas (2DEG) Hall probes for cryogenic and room temperature measurements [9, 10]. In an attempt to overcome Hall sensor dimension and drive current limitations due to carrier depletion effects in sub-micron GaAs/AlGaAs 2DEG probes at room temperature, we recently fabricated bismuth (Bi) nano-Hall and InSb micro-Hall sensors. Materials with high mobility and low carrier concentrations are desirable for optimal performance. InSb has the highest mobility at room temperature. Combination of optical lithography and focused ion beam milling is used for Hall probe fabrication. The

InSb micro-Hall probes were fabricated on high quality epitaxial InSb thin films with a thickness of 1 µm grown by MBE on semi insulating GaAs substrate [11]. InSb films have a carrier concentration of 2×10^{12} cm^{-2} and a Hall mobility of 55,500 cm^2/Vs. The process used for the micro-fabrication of the InSb Hall sensors was similar to the GaAs 2DEG sensors as reported previously [2]. Figure 2(a) shows a $\sim$ 1.5 µm size InSb micro-Hall probe with a Hall coefficient of $R_H \sim 0.034$ Ω/Gauss and a series resistance of $R_s = 2.2k$ Ω. InSb thin film micro-Hall sensors exhibit a noise level of 6–10mG/$\sqrt{\text{Hz}}$, which is an order of magnitude better than GaAs/AlGaAs 2DEG sensors.

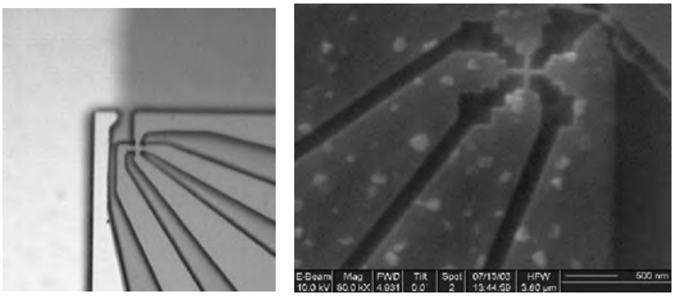

Fig. 2. Optical micrograph of a 1.5 µm InSb thin film micro-Hall (a) and a 50 nm Bismuth nano-Hall probe (b). Gold coated corner of the chip on the left of Hall cross serves as STM tip.

We have earlier achieved a spatial resolution of 120 nm [12] and recently 50 nm [13] using Bi nano-Hall sensors. However, the minimum detectable magnetic field with the Bi nano-Hall sensors was higher, 1 G/$\sqrt{\text{Hz}}$, than InSb due to high carrier concentration and low mobility at the room temperature.

3 Results

3.1 Imaging Hard Disk Media and Tape Head

Figure 3 shows the STM topography (a) and magnetic field image (b) of a CoCrTa Hard Disk sample obtained on NIST calibration sample [14] using STM tracking SHPM scans. An 800 nm GaAs/GaAlAs 2DEG Hall sensor is used for the scan. The SHPM images are quantitative giving magnetic field directly at every pixel as shown in Fig. 3(c).

Figure 4 shows the SHPM images of a sub-micron gap tape head from StorageTek at various write current levels, from 40 mA to −40 mA. Since SHPM is quantitative, it is extremely useful for measuring fields generated by tape heads or hard disk write heads, enabling engineers to design better heads and the media.

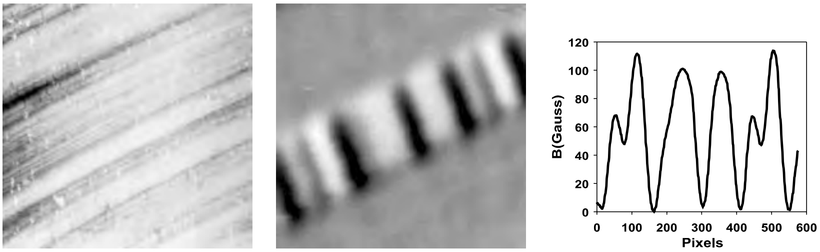

Fig. 3. Simultaneous STM (a) and SHPM image of a data track in CoCrTa Hard Disk Sample obtained in STM tracking SHPM mode. (c) shows the cross section along the arrow.

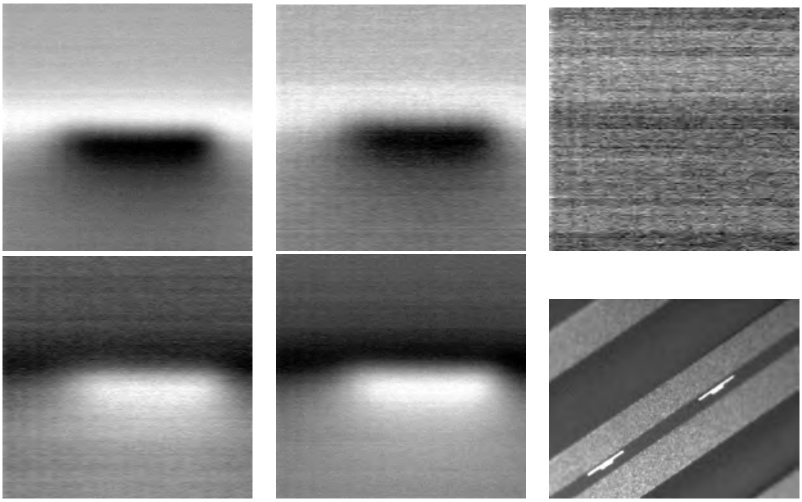

Fig. 4. 50 µm × 50 µm RT-SHPM images of 800 nm gap StorageTek Tape Head at (a) +40 mA, (b) +20 mA, (c) 0 mA, (d) −20 mA (e) −40 mA drive current. (f) optical microscope image of the tape head array.

3.2 Imaging of Magnetic Materials

Figure 5 shows the magnetic and topography images of a polycrystalline NdFeB sample obtained with the RT-SHPM simultaneously. A 800 nm size Hall sensor microfabricated from a P-HEMT wafer is used in the experiment. The sensor had a 3 mΩ/G Hall coefficient and a 25 µA DC Hall current is passed during the operation of the SHPM.

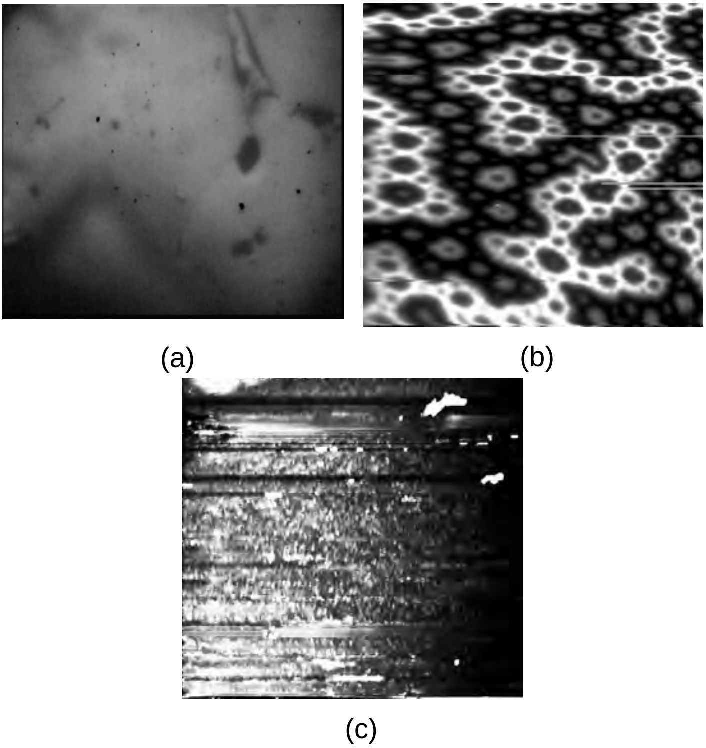

Fig. 5. Sample and the back of the Hall sensor as seen from the video microscope (a), SHPM image of the NdFeB sample, 56×56 µm scan area, black to white corresponds to -2300 to $+2400$ Gauss (b) and simultaneous STM topography of the sample, black to white corresponds to 300 nm.

3.3 Imaging of Superconductors and Magnetization Measurements

Magnetic field penetrates into superconductors as quantised fluxons called Abrikosov vortices. We have imaged vortices in YBCO and BSCCO superconductors using our LT-SHPMs. Figure 6 shows the image of vortices forming a regular triangular lattice in BSCCO single crystal [15]. SHPMs can also be used to perform local magnetization measurements, over an area defined by the Hall probe size, down to 50 nm scale. The Hall sensors are probably the smallest magnetometers that can be constructed with extremely high magnetic moment sensitivity. Moreover, one can scan the sample and measure the magnetization over an area, operating it as a Scanning Hall Magnetometer. We have also performed quasi-real time imaging to investigate how vortices penetrate into the superconductor. Figure 6 shows snapshots of images acquired at 1s intervals, showing the motion of vortices as they penetrate the

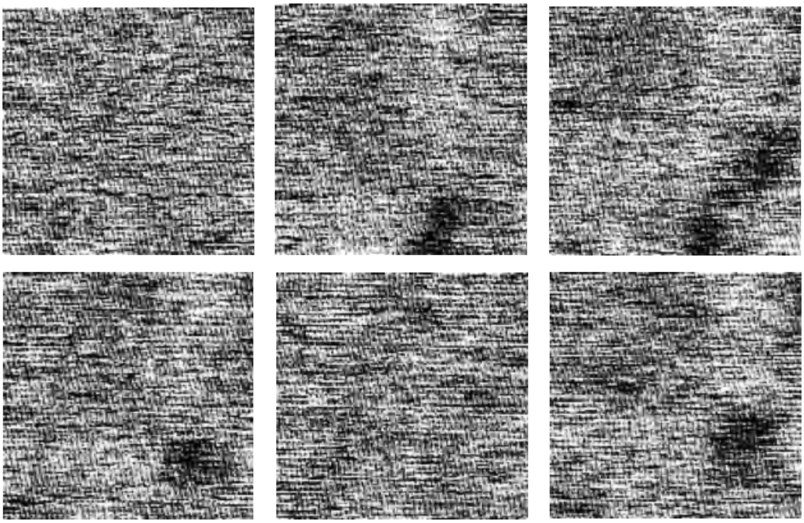

Fig. 6. Snapshots of SHPM images showing the penetration of individual vortices into BSCCO single crystal at 77 K as the Hext is cranked up to +4 Oe from 0.

crystal one by one. They stop at the pinning sites momentarily as they are move under the influence of the external field. One can make movies out of these snapshots to visualize the events more clearly.

4 Conclusion

SHPMs are becoming indispensable tools for characterizing the magnetic materials at ($\sim$ 50 nm) scale quantitatively and non-invasively. Improvements in the spatial resolution ($\sim$ 10–20 nm), time resolution ($\sim$ ps) and scan speed ($\sim$ 8–10 Frames/s) seem to be feasible, opening up new possibilities, which can not be imagined before.

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