co-workers were able to guide and steer oriented nanowires with a spatial resolution better than 300 nm (Fig. 1).

The Johns Hopkins team examined the ability of their nanowires to deliver biological ligands to cells by utilizing the tumour-necrosis factor (TNF) signalling pathway: this is a series of interactions that are important for cell death (apoptosis) and cancer progression. In this pathway, the docking of TNFα to its corresponding membrane receptor ultimately results in the activation of a transcription factor, nuclear factor-κB (NF-κB), which then translocates to the cell nucleus[7]. Amazingly, Levchenko and co-workers found that an individual nanowire, 6 μm long and 300 nm in diameter, was capable of activating NF-κB translocation in a single cell. Furthermore, they observed that NF-κB translocation only occurred in cells that were contacted by the TNFα-coated nanowires, whereas the neighbouring cells were not affected.

The limitation with any technique, including this one, is the degree to which the experimental method unintentionally perturbs the system being investigated. Parameters such as the electric-field strength or fluid shear can be undesired stimuli, potentially confounding the study of signalling responses. Levchenko and co-workers[1] make progress in addressing this issue by performing live/dead assays. Although they find that most cells in the culture are still viable six hours after being subjected to the electric fields, the exposure times are relatively short, and more extensive studies are needed to determine whether this technique can be used over longer periods of time to, for example, deliver a sequence of different molecules to a target cell.

If electric tweezers are shown to be unobtrusive to the cellular environment, they may hold great promise for analysing the stimulation of individual cells or groups of cells. By combining several stimuli with spatial and temporal control over their delivery, it may be possible to better understand receptor processes in biological systems. Furthermore, previous work by the Johns Hopkins group on the control of even smaller structures (multiwall carbon nanotubes with diameters between 20 and 50 nm) hints towards the possibility of stimulating increasingly nanoscopic regions of cellular structures[8]. Were he still alive, Robert Hooke would surely be amazed to find that the tools of modern science have transformed his 'monastic cells' into gigantic and ornate halls, and that scientists continue to be fascinated by their magnificent architecture. ❐

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DATA STORAGE

# The third plasmonic revolution

Combining nanostructured magnetic media with nanoplasmonic antennas has propelled commercially viable data-storage densities beyond one terabit per square inch.

Daniel O'Connor and Anatoly V. Zayats

From stone tablets, papyrus scrolls and books to computers and mobile phones, it is the nature of human civilization to record and pass on information. Since their invention in 1957, magnetic hard disk drives (HDDs) have remained at the forefront of data-storage technology, providing a robust and versatile way to quickly record, store and retrieve vast amounts of digital data at a minimum cost. The first HDDs had a capacity of 2 MB and an areal recording density of 2 Kb per square inch, which corresponded to each bit cell occupying an area of approximately 0.5 × 0.5 mm$^2$. The latest generation of HDDs are capable of storing several terabits (Tb) of information, with individual bit cells having areas of less than 100 × 100 nm$^2$, and this information can be accessed on timescales of less than 1 nanosecond per bit. Nevertheless, new approaches are needed to keep up with the ever-growing demand for information. Writing in *Nature Photonics*, Barry Stipe and co-workers[1] at Hitachi research centres in the US and Japan describe how to further increase the capacity of magnetic HDDs and reduce the bit-cell size by combining two new methods of magnetic recording: plasmonic near-field transducers and bit-patterned magnetic materials (Fig. 1).

Magnetic recording media are made from ferromagnetic materials, such as Fe, Co, Ni and their alloys, and information is stored in localized regions (magnetic domains) that retain a spontaneous magnetization that can be aligned in a certain direction by applying an external magnetic field. The main limitation to increasing the areal density of magnetic storage is the magnetic material used to store the data. If the area of the bit cell is reduced, the number of grains within it becomes smaller and smaller until it is no longer possible to distinguish between the grains and the cells. The solution is to reduce the grain size, but below a certain size the grains become unstable and their magnetizations can change arbitrarily owing to thermal effects. To avoid this superparamagnetic limit and take advantage of smaller grain sizes, one needs to use materials with a higher magnetocrystalline anisotropy energy — the energy required to change magnetization from one direction to another. However, this means that higher switching fields are needed to write the data, but these fields are limited by the magnetic properties of the materials in the recording head.

An approach called energy-assisted magnetic recording[2] has been proposed to overcome this problem. When the temperature of a magnetic material that cannot be written to at room temperature is increased towards its Curie temperature, the magnetic field needed to change magnetization (the coercive field) may be reduced below the available switching field. This approach is also called heat-assisted magnetic recording (HAMR) by Seagate[3], or thermally assisted magnetic recording (TAR) by Hitachi[1]. Thus, if it is possible to heat the medium only when and where data is being written to, then one could effectively ignore the superparamagnetic limit through the use of small grains of highly coercive materials. Achieving this would lead to the creation of higher-density HDDs with vastly improved bit lifetimes.

Using light to provide the energy for heating the magnetic material would seem the most logical approach because it requires no direct mechanical contact with the medium, and can be relatively easily integrated in a write head. Taking into account the amount of energy that must be deposited within the transit time of the write head over the bit cell, a minimum incident power of 1–2 mW is needed to be delivered to a spot size of about 10 nm on the storage medium. Nanoscale light sources based on apertures have been used in scanning near-field microscopy for many years, but they cannot provide the power throughput needed because the transmittance scales as $1/d^4$, where $d$ is the aperture diameter. In apertureless near-field microscopy, however, plasmonic antennas are routinely used to provide significant light confinement with high efficiency. Several analogous approaches have been proposed recently for data-storage applications, all based on the use of metal nanoparticles[1,3,4] or metal waveguides[5,6] as nanoscale antennas to localize and enhance the electromagnetic field, and also to act as a resonator to channel optical energy into subwavelength nanoscale spots. This is achieved by coupling the light to surface plasmons (free-electron excitations in the metal).

Metal nanoparticles were first used (unknowingly) to control the scattering of light by the ancient Romans, as shown by the Lycurgus cup, and later in the stained glass of medieval churches. A second generation of plasmonic technology includes chemical sensors and biosensors (including pregnancy tests). The same ability of metal nanostructures to confine and enhance electromagnetic fields is now being explored for applications in magnetic data storage in a third generation of plasmonic devices with commercial potential.

Being integrated next to a magnetic write head and illuminated by a continuous[3] or pulsed (one pulse per bit)[1] laser, plasmonic transducers have been shown to provide sufficient light concentration to locally increase the temperature of the magnetic medium by about 300 °C for a period of 1 ns, which is enough to allow data to be recorded on a granular medium made of a highly coercive magnetic material. However, the areal density was limited to about 0.3 Tb per square inch owing to the optical spot size of approximately 50 nm (which is impressively small because the laser wavelength was 830 nm).

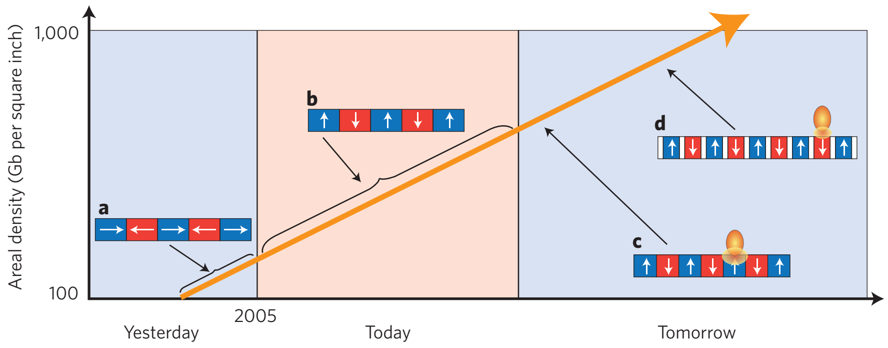

**Figure 1 |** Areal density (on a log scale) versus year for different forms of magnetic HDD technology. Gb = gigabits. The orange arrow shows the potential increase of areal density with time. **a**, Longitudinal recording relied on in-plane-oriented magnetic domains on a granular medium. **b**, Perpendicular recording on a granular medium uses smaller, off-plane-oriented magnetic domains. The use of low-magnetic-anisotropy materials means that this approach is subject to the superparamagnetic limit. **c**, Temperature-assisted perpendicular recording on a granular medium. The use of high-magnetic-anisotropy materials means that this approach is not subject to the superparamagnetic limit, and it should, in principle, be possible to reach areal densities of 100 Tb per square inch by using grains with sizes of 2–3 nm (ref. 7). **d**, Temperature-assisted perpendicular recording on an artificially patterned medium. Stipe and co-workers[1] report areal densities of about 1 Tb per square inch, and this combined approach has the potential to become the next-generation HDD technology.

To increase the areal density, the Hitachi group proposes using a plasmonic transducer with a bit-patterned magnetic medium rather than a conventional granular medium. For bit-patterned media, nanoscale patterning is used to create bit cells defined by magnetic islands about 20 nm in size, arranged in a hexagonal lattice. Thus far, neither bit-patterned media nor temperature-assisted recording has, on their own, beaten commercial perpendicular-recording-based HDD, but in combination they can achieve an unprecedented areal density of more than 1 Tb per square inch. The advantages of the combined approach are many-fold; some practical, some fundamental. Among the latter, the most important is the use of two metallic particles separated by a nanoscale gap: one particle is the transducer and the other is the magnetic island on the disc. This is effectively equivalent to a composite antenna with the field distribution and the enhancement determined by both particles. This immediately leads to stronger light confinement and more efficient energy deposition than for continuous granular media. Moreover, because the particles corresponding to different bit cells are now physically separated, the resulting temperature rise is mainly limited to one individual bit cell. These two advantages give the combination of a bit-patterned recording medium and plasmonic near-field transducer an edge in the race to define the future of magnetic data storage.

There are lots of technical difficulties to overcome before such data-storage devices will hit the stores. Important challenges include: making large chip-scale areas of bit-patterned medium inexpensively; optimizing the efficiency of the transducer to reduce wasted light energy; preventing the plasmonic particle and the magnetic medium from degrading owing to photothermal and thermo-mechanical effects arising from the enormous amount of heat being channelled through the write head; and ensuring fast write speeds (which will be limited by how fast the medium can be heated and cooled). Nevertheless, the combination of bit-patterned media and plasmonic technology has the potential to become the future of digital data storage. It is impossible to say which plasmonic transducer will win the competition or what the recording medium will look like, but in a few years' time when your computer displays the message 'HDD is heating up', it will not be a warning but an assurance that your data are being safely saved. ❐

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