Combined precision

How to provide ultimate spatial resolution and sensitivity in magnetic imaging of nanostructures.

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A new measurement technique uses a combined atomic force and confocal microscope thus paving the road towards quantitative magnetic imaging of nanostructures with unprecedented spatial resolution and sensitivity. This is especially relevant for new developments in data storage.

Both high-technology industry as well as fundamental research in many different fields are tackling smaller and smaller feature sizes for their applications. Driven by the need to e. g. achieve higher storage densities for next generation storage media, or to implement new quantum information processes, the precise characterization of nanometer-sized objects is of greater importance than ever before. In particular for magnetic imaging, many different sophisticated techniques with very high sensitivity have successfully been used for more than two decades. But until recently, these were either invasive and non-quantitative (such as magnetic force microscopy, MFM), or limited with respect to their spatial resolution (such as scanning SQUID microscopy and scanning Hall probe microscopy, SHPM). The unique properties of the so-called 'nitrogen-vacancy' (NV) defect centers in diamond however hold the promise of a completely new generation of non-invasive and quantitative nanoscale magnetometers with unmatched sensitivity whilst retaining ultra-high spatial resolution. The first results with sophisticated combinations of confocal and atomic force microscopy have already been published [1-4].

After decades of evolution in magnetic imaging, combining the sensitivity needed to detect single electron or nuclear spins with a spatial resolution of a few nanometers may soon get within reach of current state-of-the-art instrumentation: NV color center based nanomagnetometry, which operates on the principle of optically detected magnetic resonance (ODMR) is commonly considered to be the most promising candidate to achieve this goal. While there is huge scientific activity to reliably prepare appropriate nano-diamonds with tailored NV center characteristics and to attach them to atomic force microscope tips, attocube as a commercial supplier of scanning probe microscopes is complementing these efforts by providing an ideal platform for ODMR: the attoAFM/CFM combines a cantilever based atomic force microscope (AFM) with a high-numerical aperture confocal microscope (CFM) and is built entirely from non-magnetic materials (**Fig. 1**).

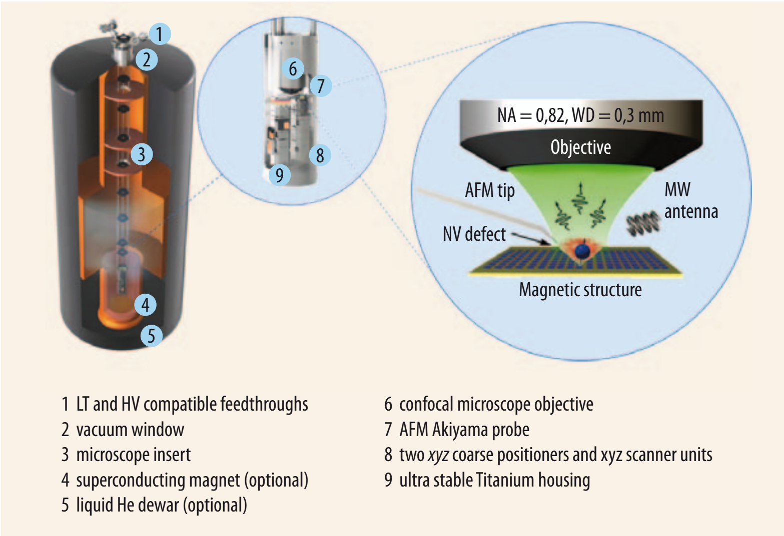

Fig. 1 Schematics of the combined atomic force and confocal microscope with NV-center grafted onto AFM tip.

NV centers in diamond have been one of the hot topics in physics for several years. When two adjacent carbon lattice atoms in diamond are replaced by one nitrogen atom and one vacancy, they build an atomic-sized spin system which shows spin-dependent photoluminescence, and can be used as a well-controlled single photon source. At the same time, it possesses exceptionally long spin coherence times, which translate into extremely high magnetic sensitivities down to about 3 nT at 100 s averaging time [2]. This also enables research on these defects at room temperature, making experiments as well as possible applications much easier. Since magnetic signals quickly die off on relatively short length scales, the small size of this potential sensor also offers the ability to bring it very close to the region of interest, thus contributing to higher sensitivity.

In order to employ the outstanding properties of NV centers for magnetic imaging, a combination of an AFM (which controls the position of the sensor with respect to the sample surface), and a confocal microscope (which provides the optical spin state preparation and readout in reflection mode) is used.

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Although not yet commercially available, nano-diamonds hosting a single NV center are now routinely grafted onto a conventional AFM tip in many research laboratories, yet they still require sophisticated methods and experienced researchers.

The attoAFM/CFM discussed here features a so-called Akiyama probe to investigate any tip-sample interaction forces on the nanometer scale. These probes combine the convenience of conventional AFM cantilevers with electrical deflection detection via a tuning fork, and thus eliminate the need for a laser-based AFM detection mechanism. As a result, the AFM tip is so compact that it fits in between the sample and an objective with ultra-high numerical aperture and low working distance. The tip is typically operated in non-contact mode using a phase-locked loop (PLL) to excite the probe at resonance and track any frequency shifts due to tip-sample interactions. The PLL keeps this shift at a constant value while scanning over the surface and hence keeps the force on the tip constant. Simultaneously to the information provided by the AFM probe, the CFM reveals complementary optical information of the sample surface. To maintain a constant distance between the low-temperature compatible lens and the sample, upon force changes, only the AFM tip is adjusted in height by a dedicated scanner.

One of the major advantages of this new instrument is its outstanding drift stability of about 10 nm/hr (even at room temperature, which is even more challenging than at well thermalized low temperature), which builds the basis for high-resolution imaging. Local magnetic fields are subsequently measured via the Zeeman shifts of

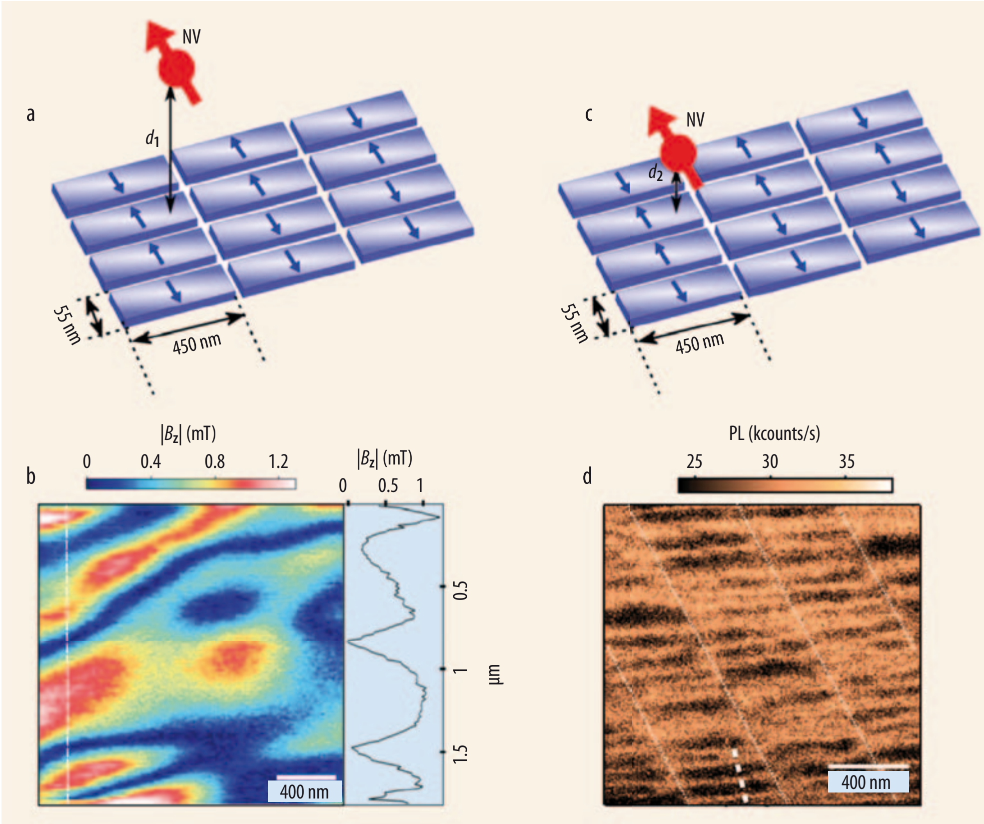

Fig. 2 Here are two examples for magnetic imaging of a hard disk sample with random bit orientation: Quantitative imaging using ODMR based method with NV-center scanned at $d_1 = 250$ nm above the sample (a) yields a quantitative magnetic field distribution (b) recorded with the lockin technique (13-nm pixel size, 110-ms acquisition time per pixel). The frame on the right shows a line-cut taken along the dashed white line in the image. The all-optical method with NV center closer to the sample surface (c) yields a photoluminescence image (d, no microwave field applied) recorded with the NV-scanning probe magnetometer in tapping mode (8-nm pixel size, 20-ms acquisition time per pixel). Comparisons with simulations indicates that the tip height is roughly $d_2 = 30$ nm. Fine white dotted lines are plotted along the direction of the hard disk tracks as a guide for the eye [3].

the NV defect spin sublevels which are directly proportional to the local magnetic fields encountered by the tip. This condition can be detected by a decrease in photoluminescence intensity of the NV-center under resonant microwave excitation, referred to as ODMR (**Fig. 2**). Using a lock-in technique allows tracking of the resonance shift while rastering the sample, and thus enables recording a local iso-magnetic field map with nanometer resolution [3].

More details on the different experiments can be found in [4-6], while the combined atomic force / confocal microscope is described on the attocube homepage [7].

References

[1] *G. Balasubramanian* et al., Nature **455**, 648 (2008)
[2] *J. R. Maze* et al., Nature **455**, 644 (2008)
[3] *L. Rondin* et al., App. Phys. Lett. **100**, 153118 (2012)
[4] *P. Maletinsky* et al., Nature Nanotechnology **7**, 320 (2012)
[5] *M. Romalis*, Nature **455**, 606 (2008)
[6] *C. Degen*, Nature Nanotechnology **3**, 643 (2008)
[5] www.attocube.com/nanoSCOPY/afm_cfm.html