Low Temperature
Scanning Probe Microscopes

© 2012, attocube systems AG - Germany. attocube systems and the logo are trademarks of attocube systems AG. Registered and/or otherwise protected in various countries where attocube systems products are sold or distributed. Other brands and names are the property of their respective owners.

attocube systems AG | Königinstrasse 11a (Rgb) | D - 80539 München | Germany
Tel.: +49 89 2877 809 - 0 | Fax: +49 89 2877 809 - 19 | info@attocube.com
www.attocube.com

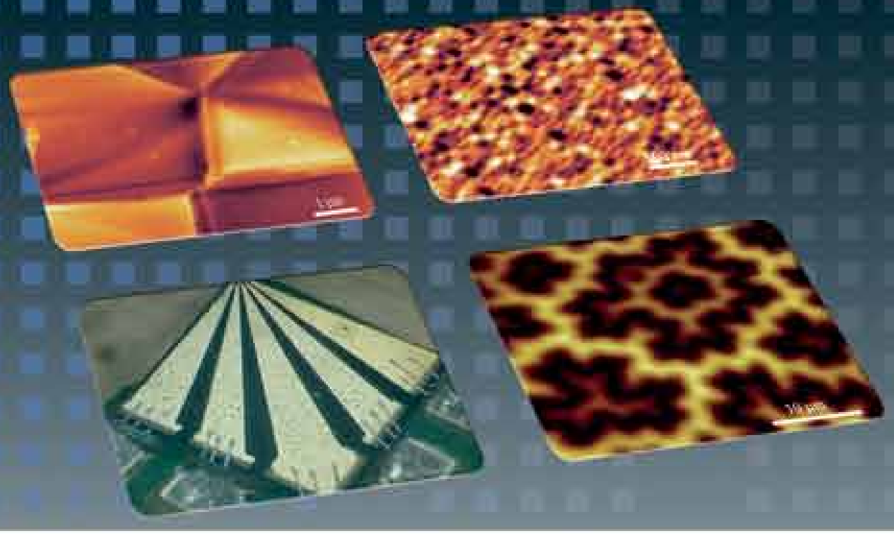
Brochure version: 2012 - 01

attocube
pioneers of precision

nanoSCOPY

nanoSCOPY

Low Temperature
Scanning Probe Microscopes



attoMFM/SHPM

Magnetic Force and Scanning Hall Probe Microscopes

attocube
pioneers of precision

Magnetism on the Nanoscale

magnetic force (MFM) and scanning hall probe microscopy (SHPM)

Magnetic imaging on small length scales has long been an important asset in fundamental research of various magnetic materials and superconductors. Spearheaded by Bitter decoration in the 1960's, magnetic imaging is nowadays ruled by much more sophisticated techniques such as Magnetic Force Microscopy (MFM) and Scanning Probe Microscopy (SHPM). With its attoMFM I and attoSHPM, attocube systems addresses both of these techniques - allowing the researcher to investigate magnetic properties with unrivalled spatial resolution and field sensitivity in environments ranging from ultra-low temperature and high magnetic fields to ambient conditions.

Historically, the **Magnetic Force Microscope** (MFM) has been derived from the Atomic Force Microscope (AFM) one year after its invention in 1986. Unlike AFM, MFM uses a magnetic tip to measure long-range magnetic tip-sample interaction forces and is typically operated with a tip-sample separation ranging from 10-100 nm.

There are two distinct modes of operation for an MFM: In constant height mode, the tip is scanned across the sample at a certain elevation. During the scan, the MFM is typically operated in amplitude mode, i.e. the cantilever is excited with constant frequency f_0 and amplitude a_0. The phase-shift measured between excitation source and cantilever then reflects the magnetic field gradient. Constant height mode is restricted to cases where the roughness of the sample surface is small compared to the tip-sample separation. For nonflat surfaces, or for cases where the tip needs to be scanned relatively close to the surface, the dual-pass mode is superior to the constant height mode.
In dual-pass mode, the tip is first scanned over the surface in close proximity and then retracted by a predefined amount. In a second scan pass, the tip follows the recorded surface topography at constant separation and the phase (or frequency) shift due to magnetic interaction forces is recorded. To avoid problems associated with drift, dual-pass mode is executed in a line-by-line fashion.

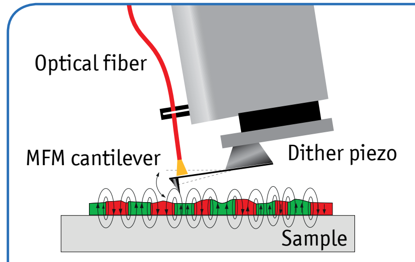
Using ultra-sharp tips on appropriate samples, the MFM achieves lateral resolution down to 10 - 20 nm*.

Compared to other magnetic imaging techniques such as MFM or scanning-SQUID, the **Scanning Hall Probe Microscope** (SHPM) is the only microscope capable of providing a non-invasive, quantitative information of the local magnetic field of a sample while yielding a sub-μm lateral resolution. Historically, SHPM is available since the late 1970s, when semiconductor Hall sensors with a two dimensional electron gas layer (2DEG) could be manufactured by modulation doping. This invention increased electron carrier mobilities to values far greater than in any other existing compound, allowing the combination of high field sensitivity with high spatial resolution – even at low temperature.

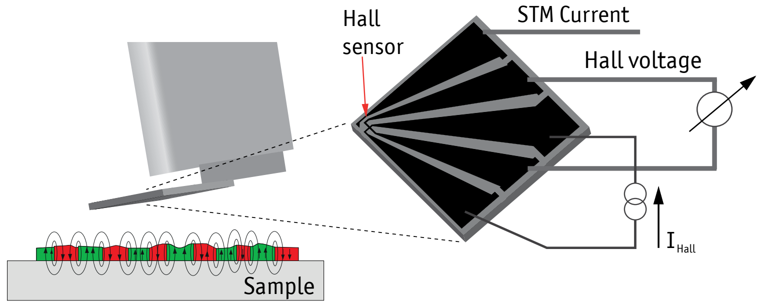
Today, the SHPM is a standard tool for the investigation of magnetic properties of a sample at both room and low temperature and is particularly, but not only, used for the investigation of superconducting materials. In a typical experiment, the Hall sensor is approached to close proximity to the sample surface and then scanned across the sample by means of a dedicated scanner. Measuring the Hall-Voltage during this process directly yields the local magnetic field which can be recorded and displayed in two or even three dimensions. For the operation of an SHPM, a mechanism to detect the location of the sample surface with respect to the Hall sensor is necessary, which is typically achieved by either measuring a tunneling current (STM-tracking SHPM) or by measuring long-range attractive forces between Hall sensor and sample (Tuning Fork-tracking SHPM).

The highest-quality **Hall Sensors** for low temperature operation existing today are made from a GaAs/AlGaAs heterostructure, created by a molecular-beam-epitaxy (MBE) growth process. attocube systems currently offers these kind of sensors with high and ultra-high resolution technology, yielding 500 nm and 300 nm spatial resolution. The thermodynamic noise limit of attocubes' sensors is typically 15 nT/Hz$^{1/2}$ at 4 K and 80 nT/Hz$^{1/2}$ at 77 K, while the practically attainable magnetic field resolution is limited to $1\times10^{-4}\ \Phi_0$ in a typical experiment, where Φ_0 is the magnetic flux quantum (2.06×10^{-14} Wb).

**M. Zech et al. Microscopy Today, Volume 19, Issue 06, pp 34 - 38.*



attoMFM I:
The attoMFM I is a cantilever-based magnetic force microscope, designed particularly for the application at extreme environmental conditions such as ultra low temperature, high magnetic field, and high vacuum. The attoMFM I uses a single-mode fiber based interferometer to detect any tip deflection with lowest noise levels and is compatible with any commercially available cantilevers.

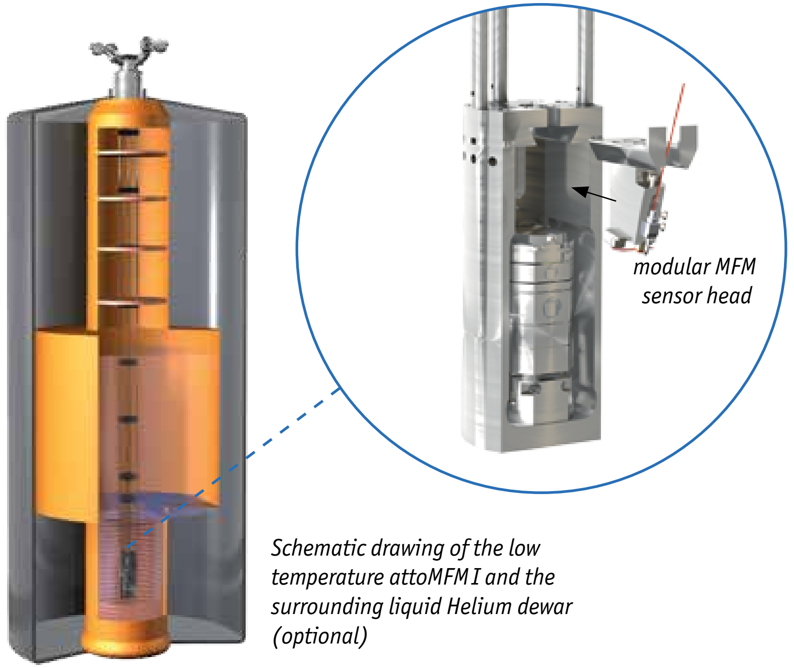


attoSHPM:
The attoSHPM is a GaAs/AlGaAs heterostructure-based Scanning Hall Probe Microscope designed for the non-invasive, quantitative detection of local magnetic fields with unrivalled sensitivity. The attoSHPM is comaptible with extreme environmental conditions, but is also suitable for room temperature application (dedicated Bi-Hall sensors for room temperature operation on request).

attoMFM I

low temperature magnetic force microscope, cantilever based

The attoMFM I is a compact magnetic force microscope designed particularly for applications at low and ultra low temperature. Based on the attoAFM I the instrument works by scanning the sample below a fixed magnetic cantilever. The magnetic force gradient acting on the tip is then determined by measuring the change in resonance frequency (FM mode) or phase of the cantilever (PM mode) with highest precision using a fiber-based optical interferometer.
Both measurement techniques are applied at a certain tip-sample distance, typically around 10 - 100 nm. In FM mode, a phase-locked loop (PLL) is used to excite the cantilever at resonance. The attoMFM I is available with capacitive or interferometric encoder for closed-loop operation.



Schematic drawing of the low temperature attoMFM I and the surrounding liquid Helium dewar (optional)

BENEFITS

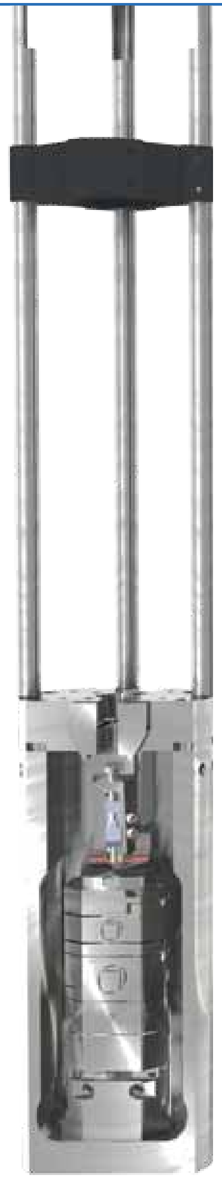
+ MFM, Contact/Semicontact/Non-Contact mode AFM, conducting tip AFM, EFM
+ upgrades available for SHPM, Confocal Microsccopy, SNOM and STM
+ 5 x 5 x 5 mm³ coarse positioning range @ 4K
+ 30 x 30 µm² scan range @ 4 K
+ high spatial MFM imaging: < 11 nm
+ large temperature range: mK .. 373 K
+ compatible with high magnetic fields (15 T+)
+ compatible with 1" and 2" clear bore size cryostats including the PPMS from Quantum Design

PRODUCT KEY FEATURES

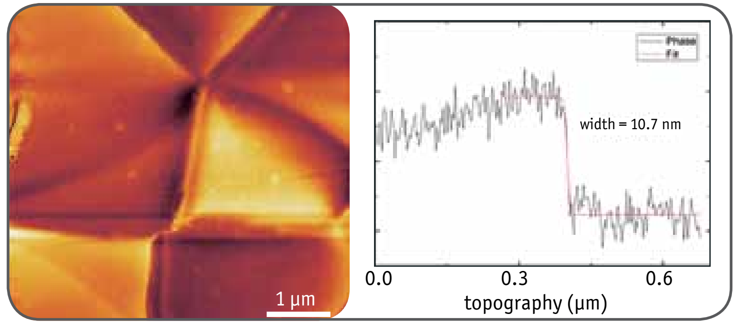
> ultra compact, highly rigid MFM head
> interferometric or capacitive encoders for closed-loop scanning available as option
> highly sensitive interferometric deflection detection
> optical inspection of sample / tip via CCD camera
> adjustment of the cantilever outside the cryostat prior to cooling the microscope

APPLICATION EXAMPLES

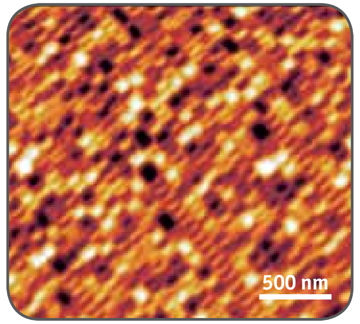
> investigation of superconductors
> domain structure studies
> materials science



Close-up of the attoMFM I microscope module



MFM measurement on 300 nm NiFe Pads showing their magnetic structure. The image was recorded at 300 K with 20 nm tip-sample separation in dual-pass mode, yielding a spatial resolution of 10.7 nm and a phase contrast of 2.3 degrees (attocube application labs, 2009).*



Magnetic phase image of a harddisc recorded at low temperature (attocube application labs, 2010).

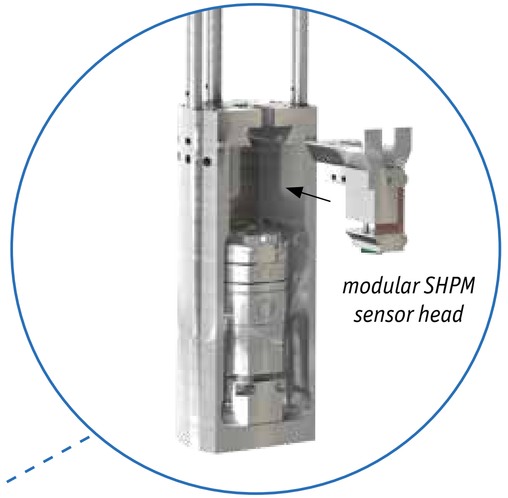
** Sample courtesy of K. Bouzehouane, Thales/CNRS, Paris*

Operation Modes	
feedback	PI feedback loop with additional PLL
imaging modes	contact mode, non-contact mode, AFM, EFM, ct-AFM, ...
Sample Positioning	
coarse range	5 x 5 x 5 mm³
step size	0.05 .. 3 µm @ 300 K, 10 .. 500 nm @ 4 K
sample monitoring	sample / tip monitoring via CCD camera and mirror (optional)
fine scan range	40 x 40 µm² @ 300 K, 30 x 30 µm² @ 4 K
closed-loop scanning option	interferometric or capacitive encoders available
Operating Conditions	
temperature range	mK .. 300 K (dependent on cryostat)
magnetic field range	0 .. 15 T + (dependent on magnet)
operating pressure range	1E-6 mbar .. 1 bar (designed for exchange gas atmosphere)
Resolution	
lateral magnetic resolution	< 20 nm
measured RMS z-noise (contact mode @ 4 K, 5ms pixel integration time)	0.05 nm (expected) 0.12 nm (guaranteed)
z deflection noise density	0.5 pm/√Hz (dependent on laser system)
z bit resolution full range mode	7.6 pm
z bit resolution small range mode	0.12 pm

attoSHPM

low temperature scanning Hall probe microscope

The attoSHPM is a compact scanning Hall probe microscope, designed particularly for operation at low temperature and high magnetic fields. At the heart of the attoSHPM, a molecular beam epitaxy (MBE) grown GaAs/AlGaAs Hall sensor measures magnetic fields with unrivalled sensitivity. Local measurements of the magnetization of a sample are obtained by scanning the sample underneath the Hall sensor and simultaneously recording the Hall voltage, directly yielding the local magnetic field.
While other local probes may outperform the Hall sensor with respect to its lateral resolution, its ability to non-invasively obtain quantitative values for the local magnetic field makes the Hall sensor a unique tool for the study of superconductors and magnetic materials. The attoSHPM is available with capacitive or interferometric encoder for closed-loop operation.



Schematic drawing of the low temperature attoSHPM and the surrounding liquid Helium dewar (optional)

BENEFITS

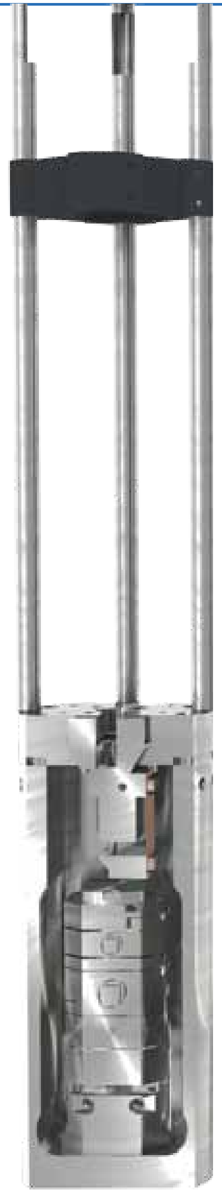
- \+ upgrades available for MFM, Contact/Semicontact/ Non-Contact mode AFM, conducting tip AFM, EFM, Confocal Microscccopy, SNOM and STM
- \+ large coarse positioning range @ 4K (5 x 5 x 5 mm^3)
- \+ large scan range @ 4 K (30 x 30 μm^2)
- \+ highest measurement sensitivity
- \+ large temperature range: mK .. 373 K
- \+ compatible with high magnetic fields (15 T+)
- \+ compatible with 1" and 2" clear bore size cryostats including the PPMS from Quantum Design

PRODUCT KEY FEATURES

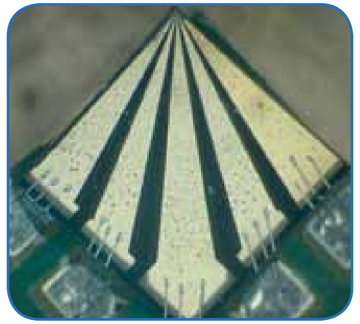
- \> ultra compact SHPM head
- \> interferometric or capacitive encoders for closed-loop operation
- \> quantitative & non-invasive magnetic measurements down to the mK range
- \> STM tracking distance detection
- \> ultra-high magnetic field resolution
- \> noise level typ. 15 nT/$Hz^{1/2}$ @ 4 K

APPLICATION EXAMPLES

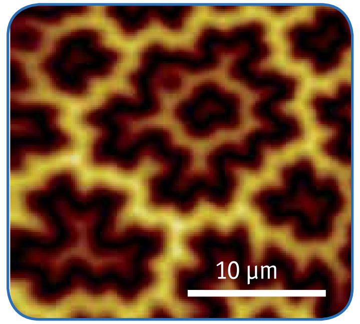
- \> vortex distribution and pinning measurements in pnicitdes, cuprates and other superconductors
- \> local field measurements on magnetic nanoparticles, bit patterned media, and other materials
- \> local hysteresis and susceptibility measurements



The attoSHPM microscope module



Close-up of the MBE grown SHPM chip, showing its Hall-sensor/STM leads and the bond wires for electrical connection to the chip carrier. The Hall sensors are available with a spatial resolution of 400 nm and 250 nm, respectively.



SHPM image of BaFeO, recorded at 4.2 K in constant height mode. The color scale spans 106 mT (black to white), while the S/N ratio of this measurement yields 2x10^5.

Operation Modes	
feedback	STM distance detection, tuning fork detection on request
imaging modes	STM tracking, constant height, or dual pass mode
Sample Positioning	
coarse range	5 x 5 x 5 mm^3
step size	0.05 .. 3 µm @ 300 K, 10 .. 500 nm @ 4 K
fine scan range	50 x 50 μm^2 @ 300 K, 30 x 30 μm^2 @ 4 K
Operating Conditions	
temperature range	mK .. 300 K (dependent on cryostat)
magnetic field range	0 .. 15 T + (dependent on magnet)
operating pressure range	1E-6 mbar .. 1 bar (designed for exchange gas atmosphere)
Probes	
design	MBE grown GaAs/AlGaAs heterostructure; Bi sensors for RT operation on request
active area	400 nm (high resolution); 250 nm (ultra high resolution)
field sensitivity	1500 V/AT
noise-equivalent magnetic field	15 nT/$Hz^{1/2}$ at 4 K and 40 µA Hall current; 80 nT/$Hz^{1/2}$ at 77 K and 40 µA Hall current
typical attainable field detection limit	15 µT typ. (Lock-In bandwidth 10 Hz at frequency 277 Hz)
Resolution	
control electronics	16 bit over selected scan range (virtually unlimited bit resolution)
lateral (xy) bit resolution at 300 K	0.46 nm at 30 µm scan range
z bit resolution at 300 K	0.065 nm at 4.3 µm scan range
lateral (xy) bit resolution at 4 K	0.18 nm at 12 µm scan range
z bit resolution at 4 K	0.030 nm at 2 µm scan range

ASC500

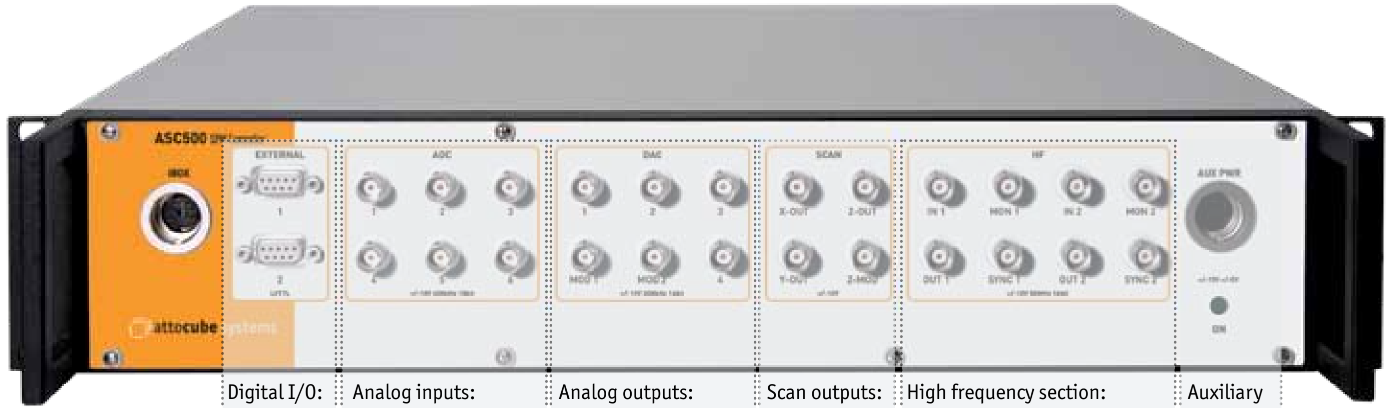
every attocube microscope comes with our state-of-the-art fully digital SPM controller

The ASC500 is a modular and flexible digital SPM controller which combines state-of-the-art hardware with innovative software architecture, offering superior performance and an unprecedented variety of control concepts. The ASC500 controller was developed with the goal to never be the limiting factor in any SPM experiment. All desirable functions and high-end specifications for conducting the experiment of your choice in MFM, SHPM, AFM, CFM, SNOM, STM, and many more are available.
Are you missing the sensitive adjustment possibilities provided by former analog SPM-units? Every ASC500 can be equipped with the ASC-iBox unit allowing fast and controlled manual adjustment of all major parameters. Now you are able to combine the advantages of manual and software control of your experiments.

KEY FEATURES

+ scan engine: 16 bit independent of scan range, 5 MHz, hardware rotation of field of view, hardware slope and drift compensation.
+ Z controller: digital PI algorithm@50 kHz, 18 bit DAC (4 pm resolution with a 1 µm scan range, theoretical limit 60 am); any signal channel as control input, setpoint modulation for PI fine tuning, inversion of feedback gain and output polarity available
+ PLL: fully digital phase locked loop with high-speed lock-in demodulator and two PI control loops (oscillation amplitude / resonance shifts)
+ 6 ADCs (18 bit)@400 kHz, 4 DACs (16 bit)@200 kHz, 2 high-frequency ADCs (16 bit)@50 MHz,analog modulation inputs, software definable transfer functions
+ supports closed loop scanning @ LT, lithography mode, spectroscopies, path mode, Q control, LabVIEW interface...

STATE-OF-THE-ART CONTROLLER (ASC500)



Digital I/O:	Analog inputs:	Analog outputs:	Scan outputs:	High frequency section:	Auxiliary power:
8 inputs 8 outputs 40 MHz	6 converters 400 kHz 18 bit	4 converters 200 kHz 16 bit 2 analog modulation inputs	3 converters 5 MHz in xy; highest resolution, z modulation input	2 independent HF channels with each: 50 MHz 16 bit input 50 MHz 16 bit output Sync output Preamplified signal monitor	+/- 5 V +/- 15 V

Looking for a suitable Cryostat ?

top-loading cryogen-free and Helium based systems with fast turn-around times | PPMS compatible

The attoDRY1000 is the perfect cryogen-free cooling platform for high resolution scanning probe experiments.

KEY FEATURES OF THE ATTODRY1000

+ ultra low vibrations
+ no liquid He needed
+ 9 T superconducting magnet (standard), vector and others magnets available on request
+ top loading design
+ cooldown time from 300 to 4 K : ~ 5h

The highly efficient attoLIQUID1000 can be the cryostat of choice for facilities with access to liquid Helium.

Interested in mK compatible MFM | SHPM or other customized complete configurations?

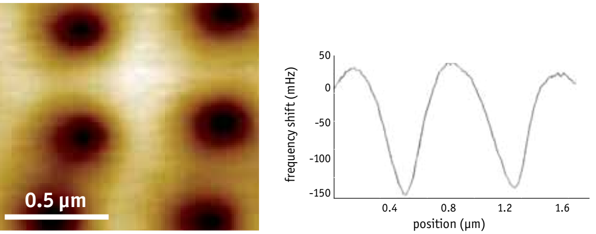
Also available for the PPMS system from Quantum Design and 1” clear bore size cryostats.

Contact attocube's sales team:
phone: +49 89 2877 809-15
email: info@attocube.com

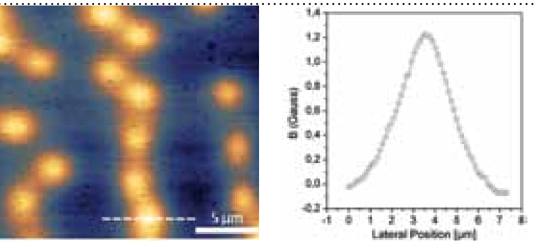
attoCRYO
nanoSCOPY
nanoPOSITIONING
attoCONTROL

Magnetic Imaging of Nanomaterials

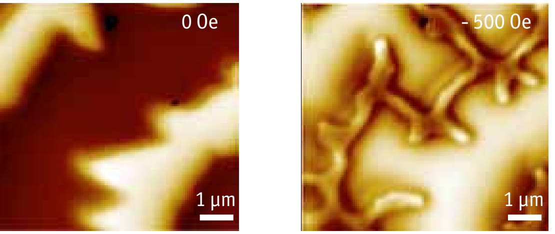
selected applications for cryogenic magnetic imaging



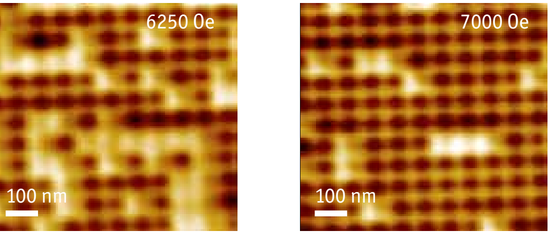
Disordered vortex lattice in the iron pnictide $Ba_{1-x}K_xFe_2As_2$ at a temperature of 4.1 K and a magnetic field of 45 Gauss. The image shows unprocessed, as-measured MFM phase data recorded at 70 nm constant height (attocube application labs, 2009; sample courtesy of Hai-Hu Wen, Chinese Academy of Science, Institute of Physics, Beijing, Republic of China).



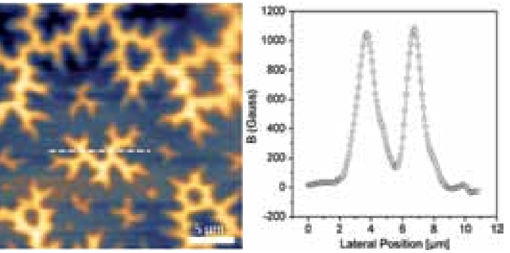
SHPM measurements on a degraded $Bi_2Sr_2CaCu_2O_{8+x}$ substrate have been performed demonstrating a strong surface pinning effects at 4.2 K and 2.5 Gauss magnetic field. The figure to the right shows a linecut through one of the vortices, displaying the field distribution approx. 100 nm above the surface (attocube applications labs, 2011; sample courtesy of A. Erb, TU Munich, Germany).



Magnetic images were measured on $Fe_{0.25}TaS_2$ at 77 K at several different magnetic fields applied perpendicular to the sample surface. The MFM measurements were performed in constant height mode and were recorded in a phase-lock-loop mode. (attocube application labs, 2009; sample courtesy of Prof. Sang-Wook Cheong , Rutgers University, New Jersey, USA).



MFM measurements on Co-Pd dots with 50 nm diameter have been performed at 10 K inside a PPMS cryostat using the attoMFM I. Variation in magnetic field applied perpendicular to the surface allows switching domains from one magnetic state to the other. (attocube application labs, 2010; sample courtesy of Hitachi Global Storage Solutions, San Jose, USA).



The figure to the left shows SHPM measurement of a BaFeO ferromagnet at 300 K. The figure to the right shows a linecut through one of the magnetic domains, indicating the strong magnetization of the ferromagnet. (attocube applications labs, 2011; sample courtesy of R. Kramer, Grenoble).

Creating scientific impact

selected customer publications 2009 - 2011

2011

Nature (2011)	L. Robledo, L. Childress, H. Bernien, B. Hensen, P.F.A. Alkemade and R. Hanson
Nature 474, 627 (2011)	C. Latta, F. Haupt, M. Hanl, A. Weichselbaum, M. Claassen, W. Wuester, P. Fallahi, S. Faelt, L. Glazman, J. von Delft, H. E. Türeci and A. Imamoglu
Nature Physics 7, 348 (2011)	T. S. Jespersen, K. Grove-Rasmussen, J. Paaske, K. Muraki, T. Fujisawa, J. Nygård and K. Flensberg
Phys. Rev. B 83, 155305 (2011)	N.A.J.M. Kleemans, J. van Bree, A.O. Govorov, J.G. Keizer, G.J. Hamhuis, R. Nötzel, A. Yu. Silov and P.M. Koenraad
Rev. Sci. Instrum. 82, 033705 (2011)	W. Kundhikanjana, K. Lai, M.A. Kelly and Z.-X. Shen
Rev. Sci. Instrum. 82, 046107 (2011)	D. Chavan, D. Andres and D. Iannuzzi
Rev. Sci. Instrum. 82, 063901 (2011)	D.S. Gianola, A. Sedlmayr, R. Mönig, C.A. Volkert, R.C. Major, E. Cyrankowski, S.A.S. Asif, O. L. Warren and O. Kraft

2010

Nature Physics 6, 534 (2010)	N.A.J.M. Kleemans, J. van Bree, A.O. Govorov, J.G. Keizer, G.J. Hamhuis, R. Nötzel, A. Yu. Silov and P.M. Koenraad
Nature Physics 6, 707 (2010)	J. C. Sankey, C. Yang, B. M. Zwickl, A. M. Jayich and J. G. E. Harris
Phys. Rev. Lett. 105, 177403 (2010)	L. Robledo, H. Bernien, I. van Weperen and R. Hanson
Phys. Rev. B 81, 115439 (2010)	M. R. Hummon, A. J. Stollenwerk, V. Narayanamurti, P. O. Anikeeva, M. J. Panzer, V. Wood, and V. BuloviΦ
Nano Lett. 10, 2927 (2010)	T. Hoang, A.F. Moses, L. Ahtapodov, H. Zhou, D.L. Dheeraj, A.T.J. van Helvoort, B.O. Fimland and H. Weman
Nano Lett. 10, 6 (2010)	C. Metzger, S. Rémi, M. Liu, S.V. Kusminskiy, A.H. Castro Neto, A.K. Swan and B.B. Goldberg
Rev. Sci. Instrum. 81, 073904 (2010)	T.A.W. Beale, T.P.A. Hase, T. Iida, K. Endo, P. Steadman, A.R. Marshall, S.S. Dhesi, G. van der Laan and P.D. Hatton
J. Appl. Phys. 107, 084307 (2010)	D. T. Smith, J. R. Pratt, F. Tavazza, L. E. Levine, and A. M. Chaka

2009

Nature 460, 724 (2009)	S. Gröblacher, K. Hammerer, M.R. Vanner and M. Aspelmeyer
Science 325, 70 (2009)	D. Brunner, B.D. Gerardot, P.A. Dalgarno, G. Wüst, K. Karrai, N.G. Stoltz, P.M. Petroff, R.J. Warburton
Nature Photonics 3, 201 (2009)	I. Favero and K. Karrai
Nature Photonics 3, 514 (2009)	E. Rousseau, A. Siria, G. Jourdan, S. Volz, F. Comin, J. Chevrier and J.-J. Greffet
Nature Physics 5, 485 (2009)	S. Gröblacher, J.B. Hertzberg, M.R. Vanner, G.D. Cole, S. Gigan, K.C. Schwab and M. Aspelmeyer
Nature Physics 5, 509 (2009)	A. Schliesser, O. Arcizet, R. Rivière, G. Anetsberger and T. J. Kippenberg
Nature Physics 5, 909 (2009)	G. Anetsberger, O. Arcizet, Q.P. Unterreithmeier, R. Rivière, A. Schliesser, E.M. Weig, J.P. Kotthaus and T. J. Kippenberg
Phys. Rev. B 80, 245325 (2009)	D. Spirkoska, J. Arbiol, A. Gustafsson, S. Conesa-Boj, F. Glas, I. Zardo, M. Heigoldt, M. H. Gass, A. L. Bleloch, S. Estrade, M. Kaniber, J. Rossler, F. Peiro, J. R. Morante, G. Abstreiter, L. Samuelson, and A. Fontcuberta i Morral
Phys. Rev. B 79, 165413 (2009)	G.D. Scott, Z.K. Keane, J.W. Ciszek, J.M. Tour, D. Natelson
Phys. Rev. Lett. 102, 197401 (2009)	R. Osovsky, D. Cheskis, V. Kloper, A. Sashchiuk, M. Kroner and E. Lifshitz
Phys. Rev. Lett. 102, 216804 (2009)	O. Copie, V. Garcia, C. Bödefeld, C. Carrétéro, M. Bibes, G. Herranz, E. Jacquet, J.-L. Maurice, B. Vinter, S. Fusil, K. Bouzehouane, H. Jaffrés and A. Bartélémy
Phys. Rev. Lett. 102, 225503 (2009)	D. R. Southworth, R. A. Barton, S. S. Verbridge, B. Ilic, A. D. Fefferman, H. G. Craighead, and J. M. Parpia
Phys. Rev. Lett. 103, 086601 (2009)	T. Belhadj, C.-M. Simon, T. Amand, P. Renucci, B. Chatel, O. Krebs, A. Lemaître, P. Voisin, X. Marie, and B. Urbaszek
Rev. Sci. Instrum. 80, 035105 (2009)	D. T. Smith, J. R. Pratt and L. P. Howard
Appl. Phys. Lett. 94, 093113 (2009)	J. McFarlane, P. A. Dalgarno, B.D. Gerardot, R.H. Hadfield, R.J. Warburton, K. Karrai, A. Badolato, and P. M. Petroff
EPL 85, 31001 (2009)	G. Jourdan, A. Lambrecht, F. Comin and J. Chevrie
Nano Lett. 9, 2273 (2009)	S.M. Yazdanian, N. Hoepker, S. Kuehn, R.F. Loring and J.A. Marohn