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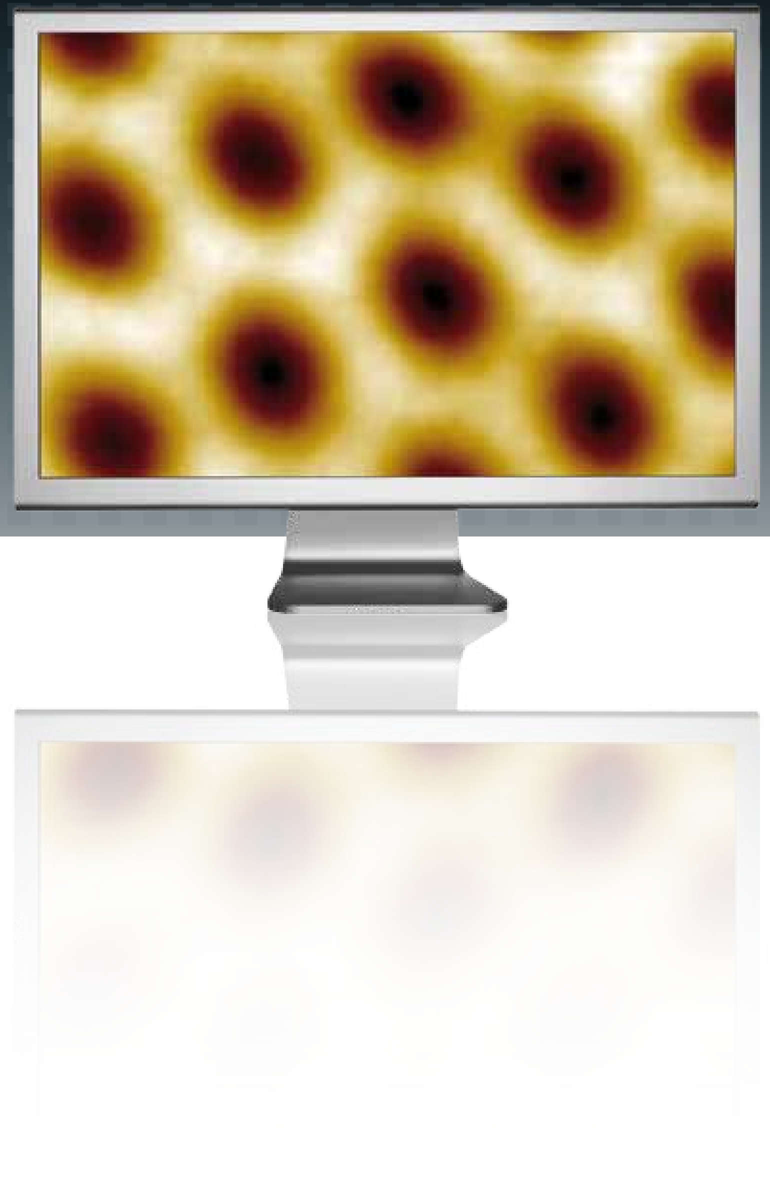
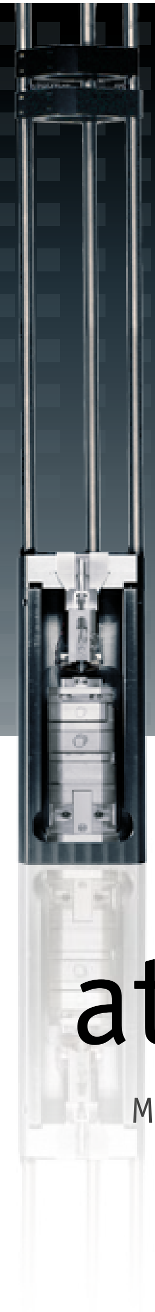
Brochure version: 2010 - 01

LOW TEMPERATURE
SCANNING PROBE MICROSCOPES



attocube systems
explore your nanoworld



LOW TEMPERATURE
SCANNING PROBE MICROSCOPES

atto**MFM/SHPM**

Magnetic Force and Scanning Hall Probe Microscopes

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01
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.

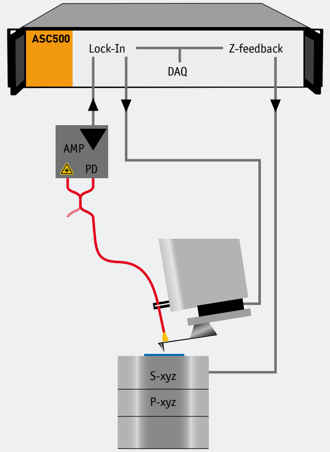
With the MFM, a lateral resolution below 50 nm is routinely observed. Under right conditions, however, a resolution of down to 11 nm has already been demonstrated* (see next page).

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.

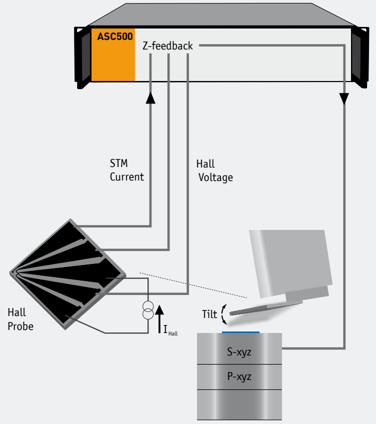
Today, the SHPM is a standard tool for the investigation of magnetic properties of a sample at both room and low temperature and is particularly, but not only, used for the investigation of superconducting materials. In a typical experiment, the Hall sensor is approached to close proximity to the sample 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 1x10^{-4} Φ_0 in a typical experiment, where Φ_0 is the magnetic flux quantum (2.06 x 10^{-14} Wb).

**attocube application labs 2009. MFM on NiFe pads in dual-pass mode with 20 nm tip-sample separation.*



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).

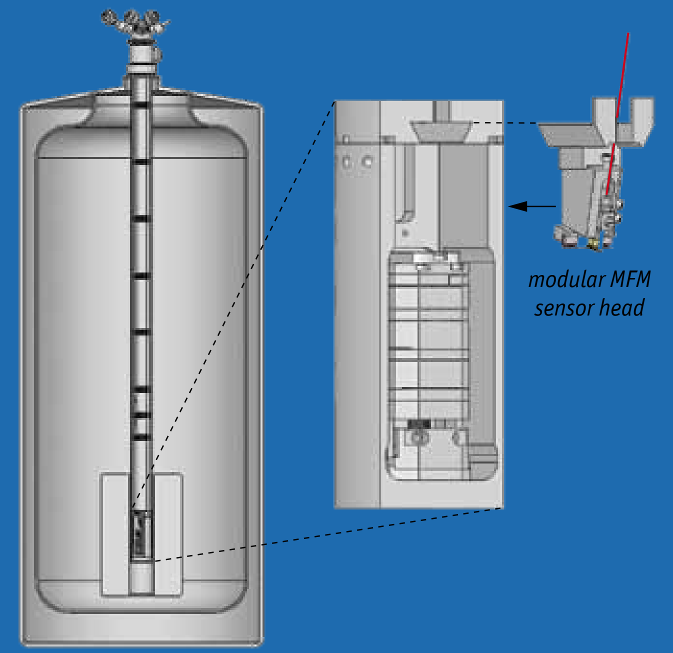
02
attoMFM I

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 a conventional atomic force microscope, 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 (AM 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 has been designed in such a way that changes in temperature or magnetic field have only minimal influence on the tip position with respect to the sample, allowing measurements in variable environmental conditions. As a further plus, the attoMFM I is fully compatible with all commercially available cantilevers.

01

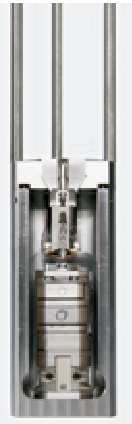


01. Schematic drawing of the low temperature attoMFM I and the surrounding liquid helium dewar (optional).

02. Close-up of the attoMFM I microscope module

03. ASC500 iBox - manual control unit for the ASC500 SPM controller.

02



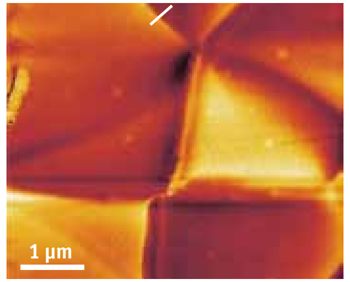
03

PRODUCT KEY FEATURES
> ultra compact MFM head
> highly sensitive interferometric deflection detection
> unrivalled stability allowing ultra high resolution imaging
> optical inspection of sample / tip via CCD camera
> adjustment of the cantilever outside the cryostat prior to cooling down the microscope

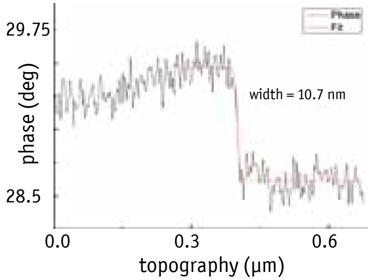
BENEFITS
> high spatial resolution imaging
> simultaneous ultra high resolution topographic and magnetic force imaging
> compatible with any commercially available MFM probe

APPLICATION EXAMPLES
> investigation of superconductors
> domain structure studies
> vortex dynamics
> materials science

04



05



Results

04 & 05. 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 (atto**cube** application labs, 2009).*
**Sample courtesy of K. Bouzehouane, Thales/CNRS, Paris*

Specifications

Operation Mode	feedback imaging modes	PI feedback loop with additional PLL contact mode, non-contact mode, AFM, MFM, EFM, SGM, ..
Sample Positioning	coarse range step size fine scan range temperature range	5 x 5 x 5 mm³ @ 300 K: 0.05 .. 3 µm @ 4 K: 10 .. 500 nm 40 x 40 x 24 µm³ 30 x 30 x 15 µm³ mK .. 300 K (dependent on cryostat)
Operating Conditions	magnetic field range operating pressure	0 .. 15 T + (dependent on magnet) 1E-6 mbar .. 1 bar (designed for exchange gas atmosphere)
Noise	measured RMS z-noise (contact mode; 4 K, 5 ms int. time) deflection noise density measured force noise (0.2 N/m)	0.12 nm (guaranteed) 0.05 nm (expected) 0.5 pm/Hz $^{1/2}$ (dependent on laser system) < 100 pN in a 1 kHz bandwidth
Resolution	lateral magnetic resolution control electronics lateral (xy) bit resolution at 300 K z bit resolution at 300 K lateral (xy) bit resolution at 4 K z bit resolution at 4 K	< 20 nm 16 bit over selected scan range (virtually unlimited bit resolution) 0.61 nm at 40 µm scan range 0.36 nm at 15 µm scan range 0.46 nm at 30 µm scan range 0.23 nm at 15 µm scan range
Sample Size	maximum	10 x 10 x 5 mm³

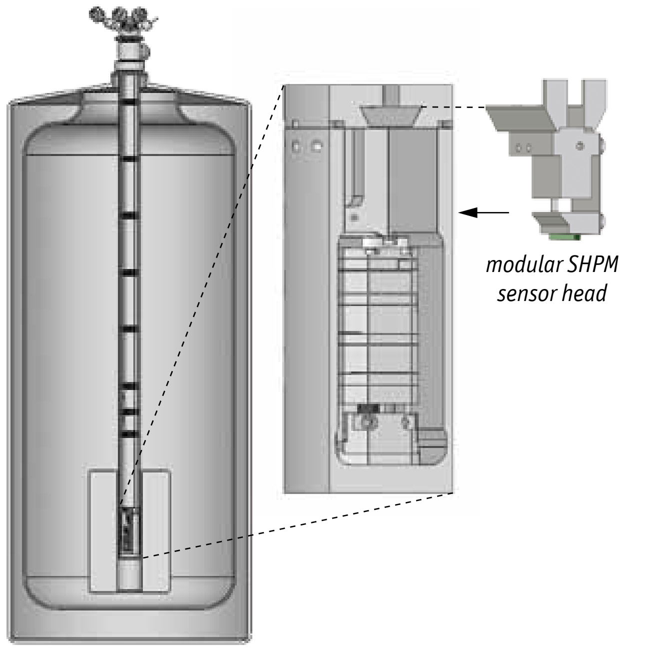
03
attoSHPM

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.

Principle - The microscope uses a set of xyz-positioners for coarse positioning of the sample over a range of several mm. The scanning motion of the sample is provided by an attocube piezo scanner, yielding a scan range of up to 30 x 30 µm² at 4.2 K. The adjustment of the Hall sensor is performed outside of the cryostat prior to cooling the microscope. The exceptional combination of materials allows absolutely stable high resolution imaging of surfaces and local magnetic fields.

01

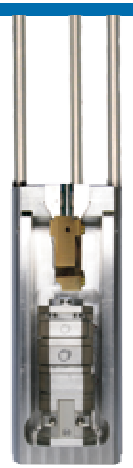


01. Schematic drawing of the low temperature attoSHPM and the surrounding LTSYS-He dewar.

02. Close-up of the attoSHPM microscope module.

03. Photograph of the attoSHPM microscope head, showing the Hall chip and its carrier (green). The tilt angle of the Hall sensor with respect to the sample can be arbitrarily adjusted between 0° and approximately 5°.

02



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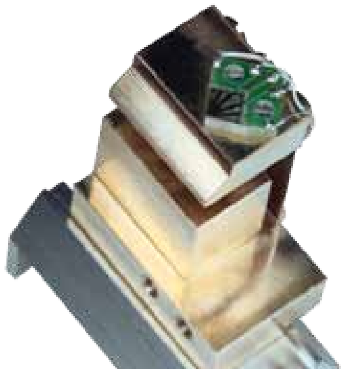
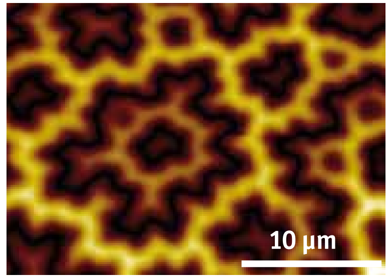


PRODUCT KEY FEATURES
> ultra compact SHPM head
> low temperature quantitative & non-invasive magnetic measurements down to the mK range
> STM tracking distance detection
> ultra-high field resolution
> noise level typ. 15 nT/Hz$^{1/2}$ @ 4 K

BENEFITS
> fits standard cryogenic and magnet sample spaces
> highest measurement sensitivity
> compatible with high magnetic fields (15 T+)
> large cryogenic scan range available (30 x 30 µm² @ 4 K)
> easily exchangeable SPM heads

APPLICATION EXAMPLES
> vortex distribution and pinning measurements in pnictides, cuprates and other superconductors
> local field measurements on magnetic nanoparticles, bit patterned media, and other materials
> local hysteresis and susceptibility measurements

04



05

Results

04. SHPM image of BaFeO, recorded at 4.2 K in constant height mode. The color scale spans 106 mT (black to yellow), while the field detection limit of this measurement is 20 µT.

05. 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 as high resolution and ultra-high resolution versions, featuring a spatial resolution of 500 nm and 300 nm, respectively..

Specifications

Operation Mode	feedback imaging modes	STM tracking distance detection, tuning fork tracking on request STM tracking, constant height, or dual pass mode
Sample Positioning	coarse range step size scan range temperature range	5 x 5 x 5 mm³ @ 300 K: 0.05 .. 3 µm; @ 4 K: 10 .. 500 nm @ 300 K: 40 x 40 x 24 µm³; @ 4 K: 30 x 30 x 15 µm³ mK .. 300 K (dependent on cryostat)
Operating Conditions	magnetic field range operating pressure	0 .. 15 T+ (dependent on magnet) 1E-6 mbar .. 1 bar (designed for exchange gas atmosphere)
Resolution	control electronics lateral (xy) bit resolution at 300 K z bit resolution at 300 K lateral (xy) bit resolution at 4 K z bit resolution at 4 K	16 bit over selected scan range (virtually unlimited bit resolution) 0.61 nm at 40 µm scan range 0.36 nm at 24 µm scan range 0.45 nm at 30 µm scan range 0.23 nm at 15 µm scan range
Hall Sensor	design spatial resolution field sensitivity noise-equivalent magnetic field attainable field detection limit	MBE grown GaAs/AlGaAs heterostructure (Bi sensors for RT operation on request) 500 nm (high resolution), 300 nm (ultra-high resolution) 1500 V/AT 15 nT/Hz$^{1/2}$ at 4 K, 80 nT/Hz$^{1/2}$ at 77 K 10 µT at 4 K typ.
Sample Size	maximum	10 x 10 x 5 mm³

04
ASC500
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.

Scan Engine:

The ASC500 uses a dedicated hardware with a 5 MHz scan generator, creating the scan voltages necessary for any Scanning Probe Microscope. The 16 bits of the xy outputs are always automatically mapped to the actual scan field, yielding a virtually unlimited bit resolution.

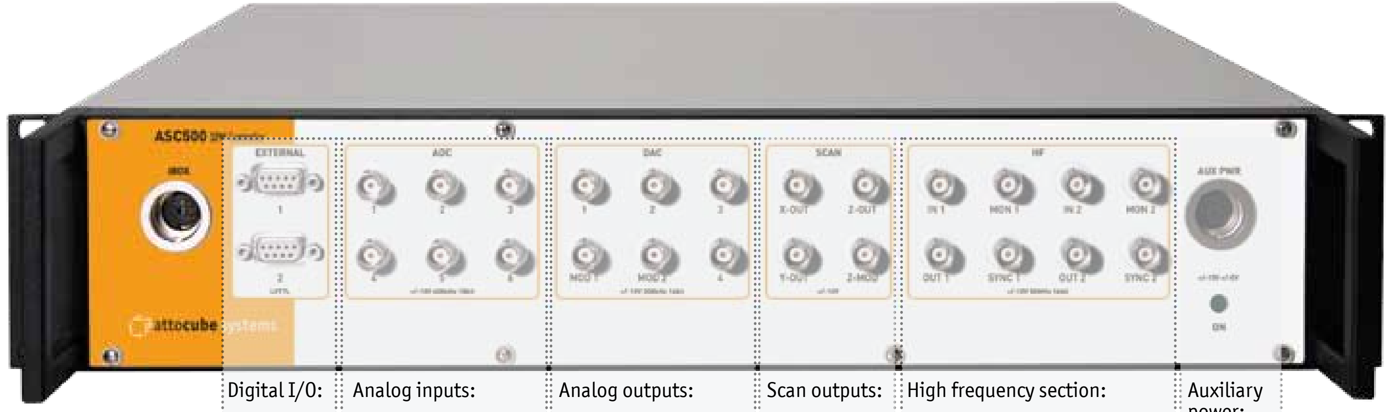
Z controller:

The z scanner output is controlled by a digital PI algorithm with a bandwidth of 50 kHz. The z output DAC has a resolution of 18 bit, yielding a 4 pm resolution on a 1 µm scan range. This resolution can be increased to a theoretical value of 60 **attometer** by limiting the control range.

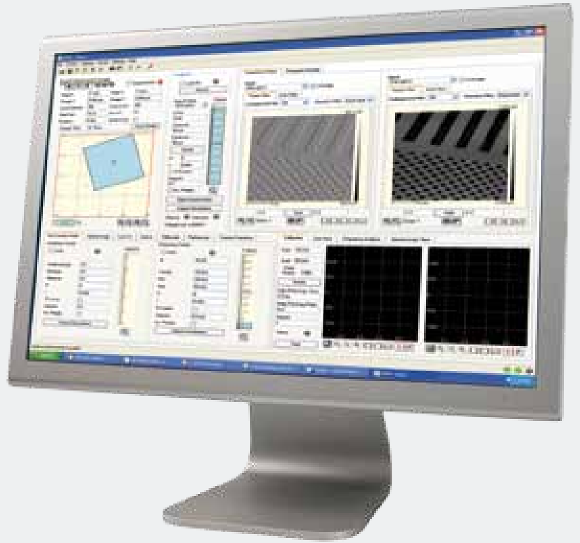
PLL

A fully digital phase locked loop (PLL) is implemented into the ASC500, taking advantage of the high frequency inputs/outputs with 50 MHz bandwidth. A high-speed lock-in demodulator and two PI control loops are used to control the amplitude of an oscillator (e.g. cantilever or tuning fork) and to follow any shifts in resonance. The frequency resolution is below 0.2 µHz in a range of 1 kHz up to 2 MHz.

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



Q Control

The ASC500 provides full control over the quality factor of any driven resonator system by means of electronic Q control. The natural Q factor of the resonator can be varied by typically more than one order of magnitude in each direction (increase/decrease).

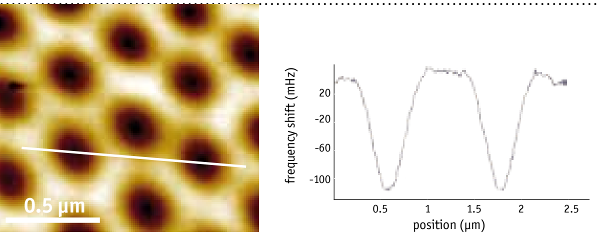
LabVIEW™ control

The new LabVIEW™ interface provides full control over all ASC500 functions. Benefits are: measurement automation, user definable experiments, and easy implementation of 3rd party instrumentation.

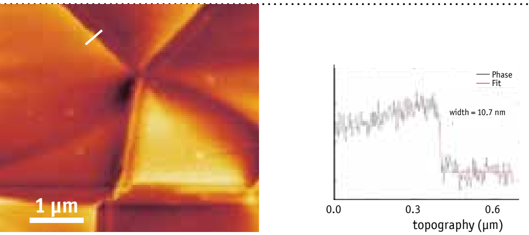
Spectroscopy

The ASC500 features advanced spectroscopy techniques such as z spectroscopy and bias voltage spectroscopy. These measurements are supported by an internal lock-in amplifier and a limiter functionality which drastically reduces the likelihood of a tip crash. Spectroscopy measurements can be automatically triggered on line, grid, or point-by-point paths. Combinations of spectroscopies can be defined in action lists.

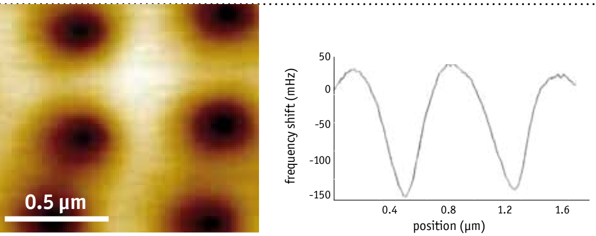
05
ATTOCUBE SYSTEMS' MICROSCOPES
OPEN UP NEW POSSIBILITIES



Hexagonal vortex lattice in optimum doped Bi-2212 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 A. Erb, Walther Meissner Institute, Germany) .



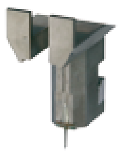
Magnetic phase image of a BaFeO sample at ambient conditions. (attocube application labs, 2009; sample courtesy of R. Kramer, Leuven University, Belgium).



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).

The ANC250 is a dedicated, ultra low noise scan voltage amplifier for piezo scanning tubes and flexure scanners. With an output noise of 20 μV_{RMS} @ a 500 kHz bandwidth, the ANC250 offers the lowest noise specs on the market. Its three input channels drive five bipolar output channels with an amplification of +/- 20. The output voltages (x+, x-, y+, y-,z) of up to +/- 200 V are ideally suited to drive piezo tube scanners.


CFM


SNOM


AFM/MFM

Switching between CFM, AFM, MFM, and SNOM is now only a matter of minutes – simply interchange the respective sensor head. The housings feature two different diameter models: the standard 2 inch version for all atto**cube** LTSYS systems and a 1 inch version to fit into most of the smaller sized low temperature systems, including the QD PPMS®.

CFM head including a low temperature objective.
SNOM head based on tuning fork technology.
Cantilever based AFM/MFM head.

06
ATTOCUBE SYSTEMS
CREATING SCIENTIFIC IMPACT

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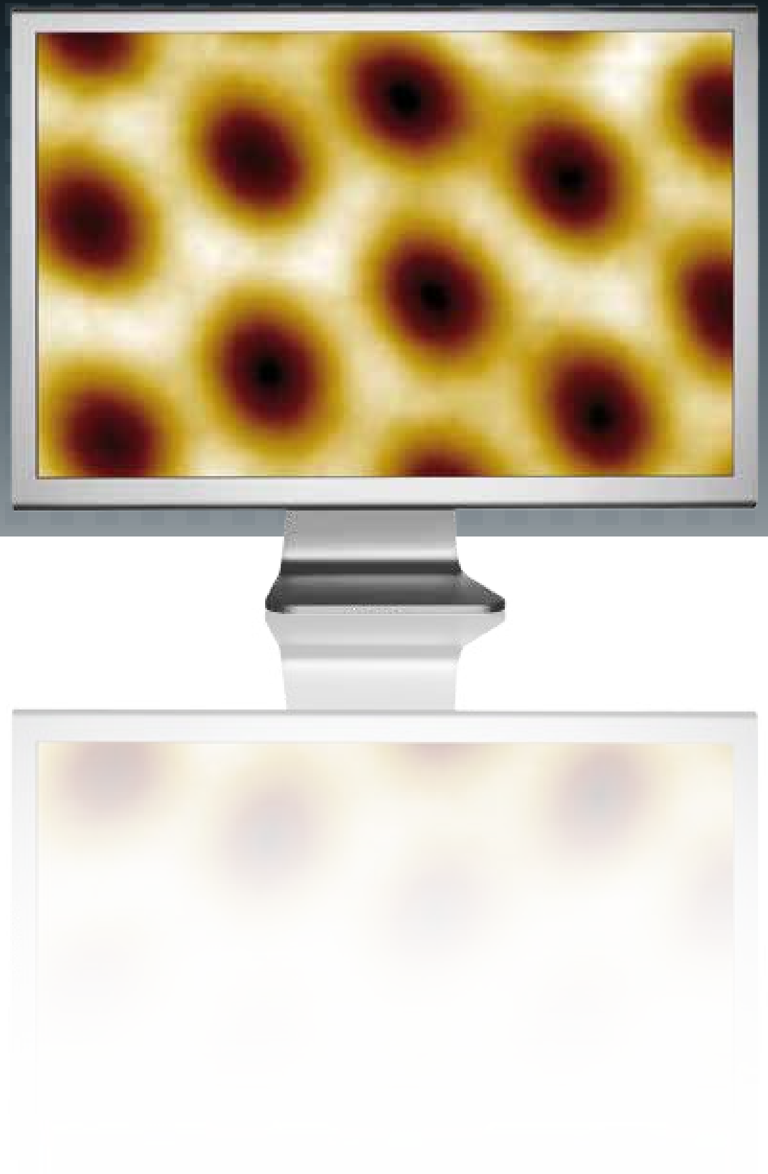
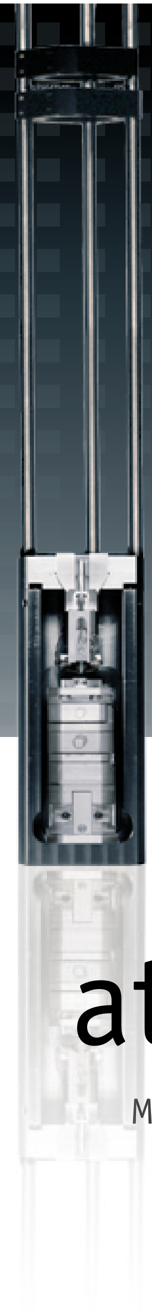
SCANNING PROBE MICROSCOPES



attocube systems
explore your nanoworld



LOW TEMPERATURE
SCANNING PROBE MICROSCOPES

atto**MFM/SHPM**

Magnetic Force and Scanning Hall Probe Microscopes

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