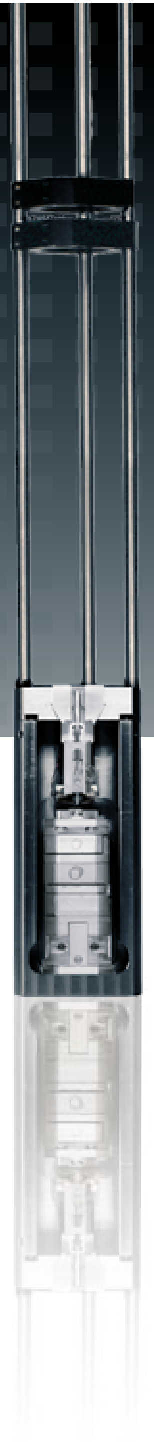
LOW TEMPERATURE
SCANNING PROBE MICROSCOPES



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explore your nanoworld

LOW TEMPERATURE
SCANNING PROBE MICROSCOPES

attoAFM

Cryogenic Atomic Force Microscopes

attocube systems
explore your nanoworld

01 WORKING PRINCIPLE

ATOMIC FORCE MICROSCOPY (AFM I, AFM III, AFM/STM, AFM/CFM)

Atomic Force Microscopy (AFM) is the method of choice for surface characterization in various fields of research, ranging from biology to life- and material science. AFM is an extremely accurate and versatile instrument enabling the investigation of surface topography, tip-sample interaction forces, and magnetic surface phenomena (MFM).

The Atomic Force Microscope (AFM) was an offspring of the Scanning Tunneling Microscope (STM) designed to measure the topography of a nonconductive sample. The AFM has undergone several enhancements over the years, allowing studies far beyond the limitations of conventional microscopes.

The simplest operational mode of every AFM is referred to as ‚contact mode'. A very fine tip mounted to the end of a small deflecting spring – known as cantilever – is brought into contact with the sample surface. The tip is then scanned across the surface in successive lines. Any vertical deflection of the tip due to short-range repulsive interaction forces can be measured and recorded with extremely high accuracy, directly yielding the surface topography. Over the years, more sophisticated AFM modes have evolved such as non-contact mode (nc-AFM) and frequency modulated non-contact mode (FM-AFM). In contrast to contact mode, the nc-AFM mode is sensitive to long range attractive forces such as caused by van-der-Waals, electrostatic, and magnetic interaction. The latter resulted in the development of the magnetic force microscope (MFM), an instrument which is nowadays widely used in applications such as vortex imaging and magnetic thin film analysis.
attocube systems' attoAFMs are designed particularly to be used at extreme environmental conditions such as ultra low temperature, high magnetic field, and high vacuum. Reliable functionality in these extreme environments is provided by implementing attocubes outstanding and patented nanopositioning modules. To perform low temperature microscopy, the attoAFMs are cooled by a controlled exchange gas atmosphere in a vacuum shielded liquid ^{4}Helium bath cryostat. For operation at even lower temperature, all attoAFMs are also available in combination with a ^{3}He insert, allowing measurements below 350 mK and with dilution refrigerator units. For applications where liquid Helium is not available or desired, the attoAFMs can be combined with cryogen-free pulse-tube based coolers.

** available on request.*

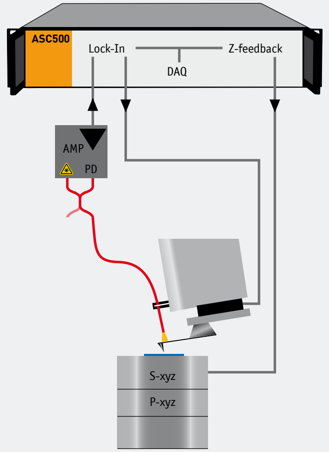
Interferometric Sensor

The deflection detection scheme for the attoAFM I microscope system is based on an all fiber low coherence interferometer. A laser diode beam coupled into a single mode fiber is used to illuminate an interferometer based on a fiber coupler. At the end of the second interferometer arm the light is transmitted and partially reflected at the AFM cantilever. Therefore, the tip interface and the fiber end face form a Fabry-Perot interferometer. A large part of the light reflected in this structure is coupled back into the optical fiber. Monitoring the intensity of the interference fringes allows to measure the tip movement. With the cantilever holder being compatible with commercially available cantilvers, the attoAFM I is perfectly suited for all standard imaging modes such as Atomic Force Microscopy (AFM), Magnetic Force Microscopy (MFM), Electric Force Microscope (EFM), etc.

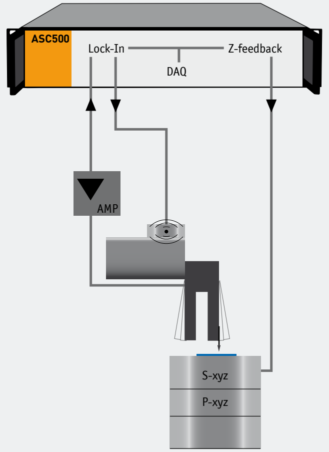
Tuning Fork Sensor

The attoAFM III uses a tuning fork sensor as detection mechanism for the tip-sample distance, allowing high resolution non-contact mode imaging without the need for any optical detection. An AFM tip is glued onto one leg of a small quartz tuning fork and forced to oscillate in horizontal direction with an amplitude of typically 50 pm. Damping of the amplitude by tip-sample interaction forces is monitored and/or used as feedback signal. The force resolution of this technique is typically equal to or better than 0.1 pN. In addition to glued tips, this system is fully compatible with the commercially available Akiyama probe.

The attoAFM III is perfectly suited for light-sensitive experiments such as Scanning Gate Microscopy on 2-dimensional electron gases.



attoAFM I:
cantilever based
This cantilever-based, compact system ensures outstanding stability enabling ultra-high resolution imaging. The adjustment of the cantilever is performed outside of the cryostat prior to cooling down the microscope. Compatible with commercially available cantilevers, this system is ideally suited for imaging modes such as AFM, MFM, EFM, etc.



attoAFM III:
tuning fork based
Based on a non-optical tuning fork detection technique, this system is ideally suited for applications where input of light is problematic. A typical application is Scanning Gate Microscopy (SGM) on semiconductor structures.

02
attoAFM I

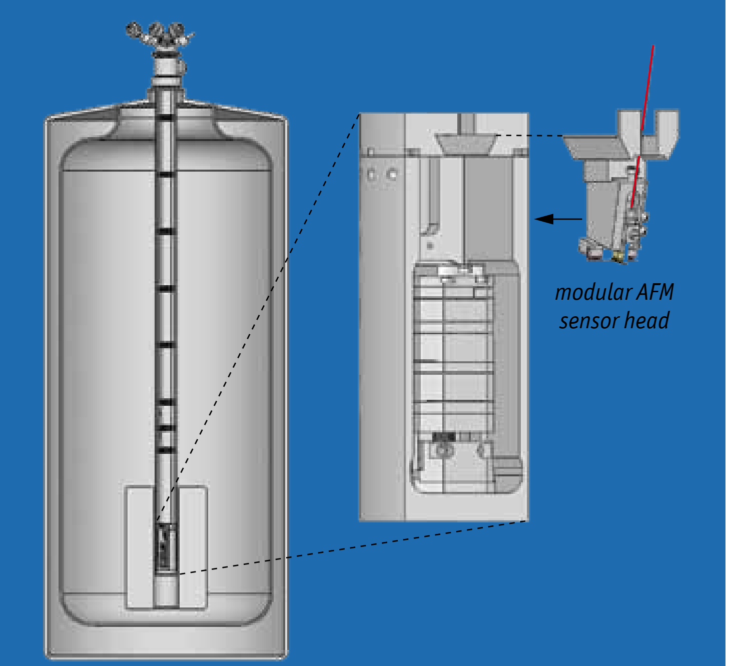
LOW TEMPERATURE ATOMIC FORCE MICROSCOPE, cantilever based

The attoAFM I is a compact atomic force microscope designed particularly for applications at low and ultra low temperature. The instrument works by scanning a sample underneath a fixed cantilever and by measuring its deflection with highest precision using a fiber-based optical interferometer. Both contact and non-contact modes are applicable. Furthermore, this system is suited for Magnetic Force Microscopy (MFM), Electric Force Microscopy (EFM), and other imaging modes.

The superior stability of the measurement head allows for the combination of the attoAFM I with cryogen free pulse-tube based cooling systems, enabling applications where liquid Helium is not available or not desired.

Principle - The microscope uses a set of xyz-positioners for coarse positioning of the sample over a range of several mm. Developed particularly for cryogenic applications, the piezo scanner ANSxy100 provides a scan range of 30 x 30 µm² even at liquid helium temperature. In the attoAFM I configuration, the adjustment of the cantilever is performed outside of the cryostat prior to cooling down the microscope. The exceptional combination of materials allows absolutely stable high resolution imaging of surfaces. Possible applications are the measurement of local sample properties such as topography, magnetic forces, or elasticity of surface structures.

01

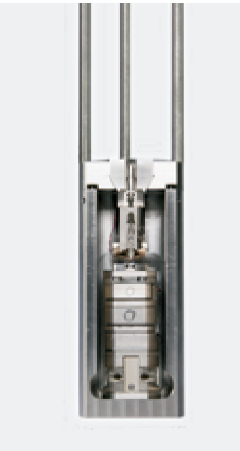


01. Schematic drawing of the low temperature attoAFM I and the surrounding liquid helium dewar (optional).

02. The attoAFM I microscope module

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

02



03

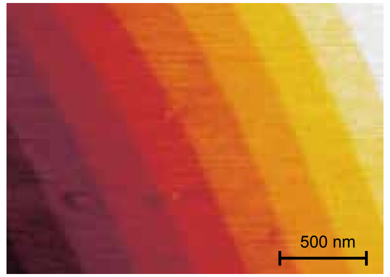
PRODUCT KEY FEATURES
- > ultra compact AFM head
- > highly sensitive interferometric deflection detection
- > unreached stability
- > optical inspection of sample / tip via CCD camera
- > adjustment of the cantilever outside the cryostat prior to cooling the microscope

BENEFITS
- > fits standard cryogenic and magnet sample spaces
- > highest measurement sensitivity
- > ultra-high resolution imaging & long-term measurements

APPLICATION EXAMPLES
- > ultra-high resolution topography imaging
- > measurement of magnetic sample properties
- > elasticity measurements
- > research on ceramics, polymers, additives, alloys, ..

04

05



Results

04. AFM contact mode image of a Si-substrate/Si0$_2$-Layer; height: 20 ± 2 nm recorded at 10 K using a closed cycle pulse tube cooler. The images were recorded with the cooler on (attocube application labs, 2007).

05. Atomically flat terraces on SrTi0 using a standard attoAFM I. The height difference for each terrace is ~0.39 nm. Acquisition time for this 150 x 150 pixel image of size 2 x 2 µm² (13 nm pixel size) was about 15 min (attocube application labs, 2007).

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; 4K, 5ms int. time) deflection noise density measured force noise (0.2N/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	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 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

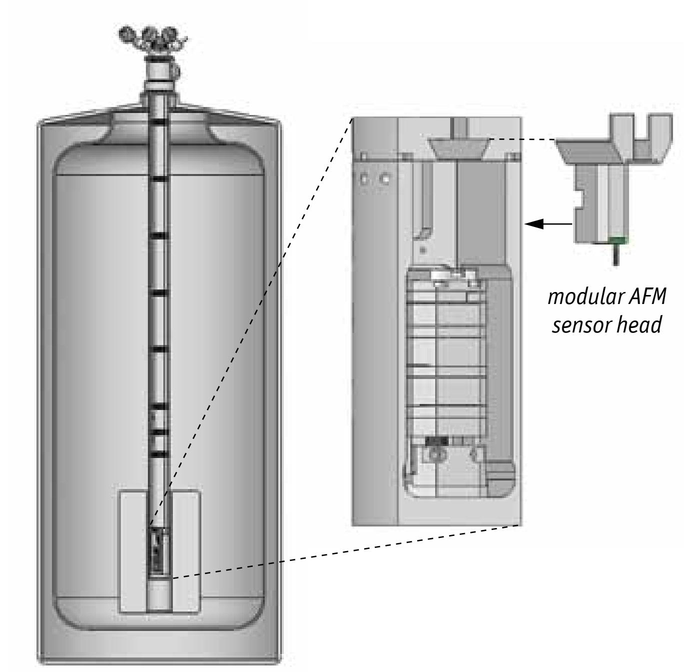
03
attoAFM III

LOW TEMPERATURE SCANNING, tuning fork based

The attoAFM III is an atomic force microscope designed particularly for applications at low and ultra low temperature. Due to the non-optical shear force detection scheme based on a tuning fork, this system is ideally suited for applications where input of light is problematic. A typical application of the attoAFM III microscope is Scanning Gate Microscopy (SGM) on semiconductor structures or on 2-dimensional electron gases. The attoAFM III microscope is also compatible with the commercially available Akiyama probe.

Principle - the attoAFM III uses a tuning fork sensor as detection mechanism for the tip-sample separation, allowing high resolution non-contact mode imaging without the need for any optical deflection detection techniques. An AFM tip is glued onto one leg of a small quartz tuning fork and forced to oscillate in horizontal direction with an amplitue of typically 50 pm. Damping of the amplitude due to tip-sample interaction when approaching the sample is monitored and/or used as a feedback signal. The force resolution of this technique is typically 0.1 pN.

01



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

02. Close-up of the attoAFM III microscope module.

03. Close-up of the tuning fork based scanning probe microscope head.

02

03

PRODUCT KEY FEATURES

> ultra compact AFM head with unprecedented stability
> highly sensitive, non-optical tuning fork sensor
> LT compatible preamplifier located in close proximity to tuning fork

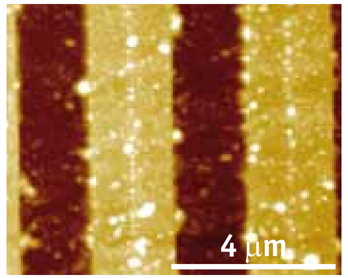
BENEFITS

> ultra high resolution imaging in non-contact mode
> high Q factor for highest sensitivity measurements
> optimized S/N ratio due to LT compatible preamplifier
> no optical alignment necessary

APPLICATION EXAMPLES

> materials science: ultra-high resolution topographic imaging
> Scanning Gate Microscopy at ultra low temperatures < 320 mK
> investigations of semiconductor structures

04



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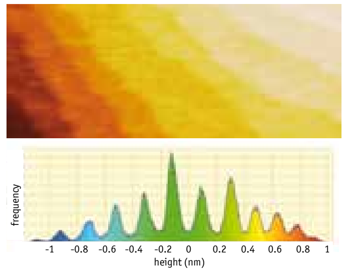


Results

04. Tuning fork AFM image of a patterned Si/SiO_2-substrate recorded at 320 mK. Height: 20 ± 2 nm recorded with the attoAFM III (attocube application labs, 2007).

05. Tuning fork AFM image of an InAs layer showing monoatomic steps with a height of 2.04 ± 0.02 Angstrom. This corresponds well to the atomic lattice constant of InAs, 2.15 Å (attocube application labs, 2007).

Specifications

Operation Mode	feedback imaging modes	PI feedback loop with additional PLL non-contact mode, EFM, SGM, ..
Sample Positioning	coarse range step size fine scan range temperature range	5 x 5 x 5 mm^3 @ 300 K: 0.05 .. 3 µm; @ 4 K: 10 .. 500 nm 40 x 40 x 4.3 $µm^3$; 9 x 9 x 2 $µm^3$ (larger range on request) 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 z-noise density	< 16 $pm/Hz^{1/2}$
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 0.065 nm at 4.3 µm scan range 0.14 nm at 9 µm scan range 0.03 nm at 2 µm scan range
Probes	probe design	etched metal wires, STM tips, Akiyama probes
Sample Size	maximum	10 x 10 x 5 mm^3

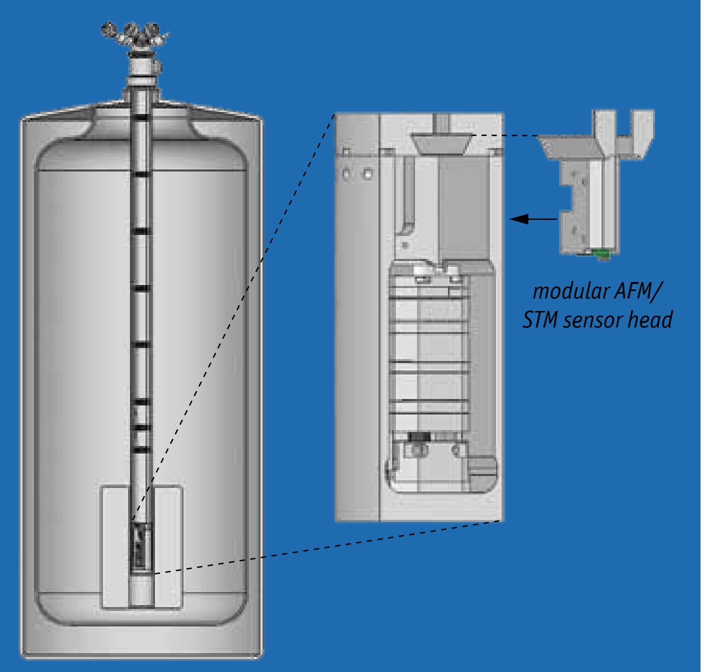
04
attoAFM/STM

COMBINED LOW TEMPERATURE ATOMIC FORCE AND SCANNING TUNNELING MICROSCOPE, tuning fork based

In the attoAFM/STM, the two worlds of atomic force and scanning tunneling microscopy are genuinely combined. In contrast to the attoAFM III, the attoAFM/STM uses a horizontally aligned tuning fork to reduce unshielded tunneling current wire length to a minimum (several millimeters in this case).
With this instrument, scanning tunneling spectroscopy measurements on generally non-conductive samples with conductive patches finally become possible.

Principle - The attoAFM/STM typically uses an ultra-sharp etched tungsten tip as a probe. The tip is glued onto the tuning fork and electrically connected to a current/voltage amplifier located on top of the experiment. A low temperature, high-vacuum compatible coaxial cable is used for this connection, guaranteeing minimum noise pickup. The instrument can be operated in AFM, STM, or combined AFM & STM mode.

01



01. *Schematic drawing of the low temperature attoAFM/STM and the surrounding PPMS dewar.*

02. *Close-up of the attoAFM/STM microscope module.*

03. *ASC500 - attocube's state-of-the-art Scanning Probe Microscopy controller featuring an open architecture and high flexibility to meet the customers' individual needs.*

02

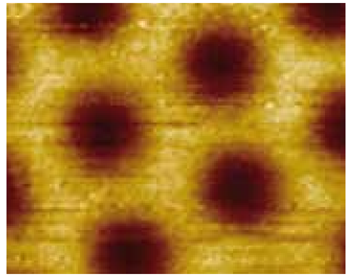
03

PRODUCT KEY FEATURES
> ultra compact SPM head with unprecedented stability
> AFM: highly sensitive, non-optical tuning fork sensor in horizontal alignment
> AFM: LT compatible preamplifier located in close proximity to tuning fork
> STM: low temperature compatible, low capacitance coaxial wiring for minimum noise pickup

BENEFITS
> ultra-high resolution imaging in non-contact mode
> high Q factor for highest sensitivity measurements
> optimized S/N ratio due to LT compatible preamplifier
> ultra low-noise tunneling current (< 40 fA/$Hz^{1/2}$ in a 7 kHz bandwidth)

APPLICATION EXAMPLES
> materials science: ultra-high resolution topographic imaging
> measurement of tunneling spectra of conducting patches on nominally non-conductive surfaces

04



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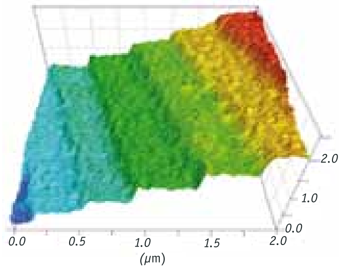


Results

04. STS vortex imaging on $NbSe_2$ at 315 mK and 1 T magnetic field. The image was recorded at a bias voltage of 1.4 mV (attocube application labs, 2009).*

05. Tuning fork AFM image of $SrTiO_3$ recorded at 350 mK with the attoAFM III (attocube application labs, 2009).

** Sample courtesy of R. Kramer, Leuven University, Belgium.*

Specifications

Operation Mode	feedback imaging modes	PI feedback loop with additional PLL AFM non-contact mode, EFM, SGM, STM, STS, ..
Sample Positioning	coarse range step size fine scan ranges 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 4.3 µm³, 9 x 9 x 4.3 µm³; @ 4 K: 9 x 9 x 2 µm³ (larger range on request), 2 x 2 x 2 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 z-noise density	< 16 pm/$Hz^{1/2}$
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) 0.46 nm at 30 µm scan range 0.075 nm at 5 µm scan range 0.18 nm at 12 µm scan range 0.03 nm at 2 µm scan range
Sample Size	maximum	10 x 10 x 5 mm³

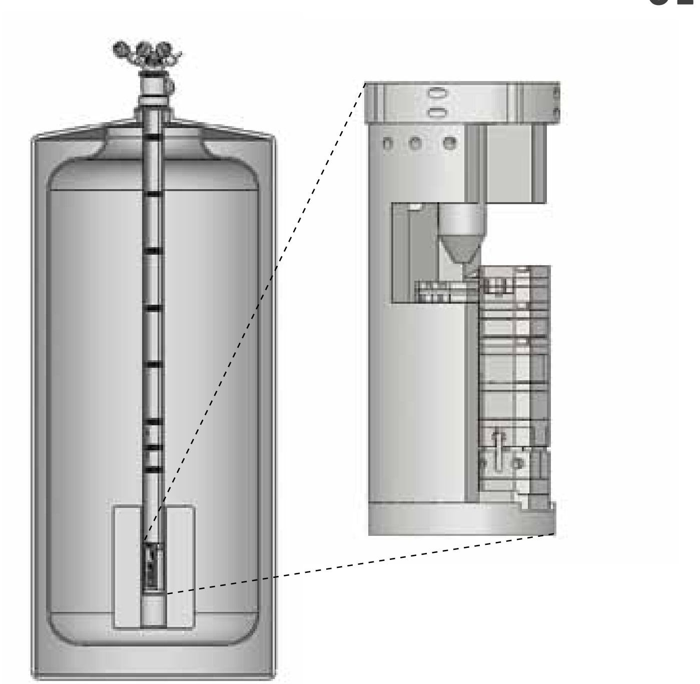
05
attoAFM/CFM

COMBINED LOW TEMPERATURE ATOMIC FORCE AND CONFOCAL MICROSCOPE, tuning fork based

The tuning fork based attoAFM/CFM not only allows fast optical investigation of the sample prior to detailed AFM studies, it also enables precise positioning of the AFM tip over small structures and optical control of the scanning process or surface manipulation. Plus, optical experiments such as Raman Spectroscopy and Tip Enhanced Raman Spectroscopy (TERS) can be conducted. Needless to say that all of these tasks can be performed in extreme environments such as ultra low temperature, high vacuum, and high magnetic field.

Principle - The attoAFM/CFM uses an Akiyama probe tip to investigate tip-sample interaction forces on the nanometer scale. The Akiyama probe is typically operated in non-contact mode using a phase-locked loop to excite the probe at resonance and track any shift in frequency due to tip-sample interactions. An additional PI controller keeps the frequency shift at a constant value while scanning over the surface. Simultaneously to the information provided by the Akiyama probe, the CFM reveals complementary optical information of the sample surface. Since the z-scanning motion is provided by a dedicated scanner on the side of the AFM, the focal distance between the low-temperature compatible lens and the sample does not change.

01



01. Schematic drawing of the low temperature attoAFM/CFM and the surrounding liquid helium dewar (optional).

02. Close-up of the attoAFM/CFM microscope module.

03. attocube offers various low temperature compatible objectives with different numerical apertures and working distances.

02

03

PRODUCT KEY FEATURES

> scan area at 4 K: 12 x 12 µm²
> independent sample scanning and scanning of the AFM module
> tuning fork based and PLL controlled systems available
> non contact measurement mode
> objectives with various working distances available (e.g. 1.56 mm or 2.91 mm)

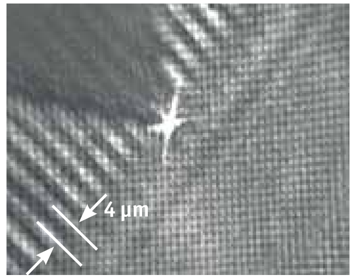
BENEFITS

> suitable for conductive and non-conductive samples
> enables exact positioning of the AFM tip
> optical access to the sample with high magnification

APPLICATION EXAMPLES

> solid state physics and quantum dot optics
> fluorescence observation
> highly stable long term experiments on single quantum dots
> biological and medical research on tissue samples in cytological and neurological applications
> fast 3D-imaging

04



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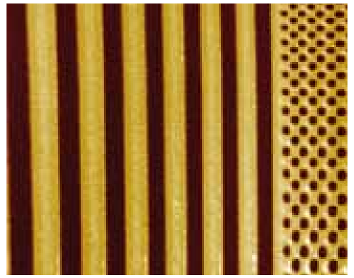


Results

04. Confocal image of the Akiyama probe in close proximity of a patterned SiO_2/Si substrate. The image clearly shows a pronounced backscattering of light at the AFM tip apex (attocube application labs, 2009).

05. Tuning fork AFM image of the SiO_2/Si substrate as imaged beforehand using the CFM (see figure above). The height modulation corresponds to 51 nm (attocube application labs, 2009).

Specifications

Operation Mode	detection mode imaging modes	PI feedback loop with additional PLL AFM non-contact mode, CFM in reflection, luminescence, fluorescence
Sample Positioning	coarse range step size scan range temperature range	3 x 3 x 2.5 mm³ @ 300 K: 0.025 .. 2 µm; @ 4 K: 10 .. 500 nm @ 300 K: 30 x 30 x 4.3 µm³; @ 4 K: 12 x 12 x 2 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) 0.46 nm at 30 µm scan range 0.065 nm at 4.3 µm scan range 0.18 nm at 12 µm scan range 0.03 nm at 2 µm scan range
Sample Size	maximum	10 x 10 x 5 mm³

06

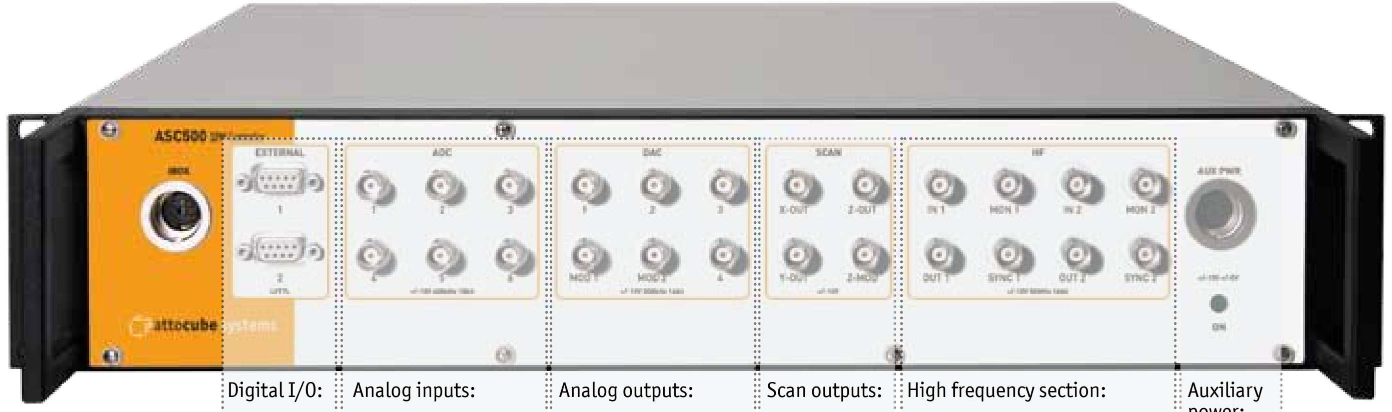
ASC500

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.

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

Scan Engine:

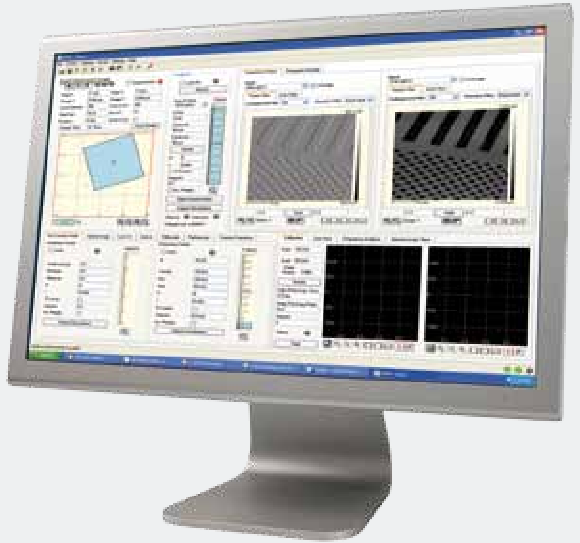
The ASC500 uses a dedicated hardware with a 5 MHz scan generator, creating the scan voltages necessary for any Scanning Probe Microscope. The 16 bits of the xy outputs are always automatically mapped to the actual scan field, yielding a virtually unlimited bit resolution.

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 is implemented into the ASC500, taking advantage of the 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 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.



Q Control

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

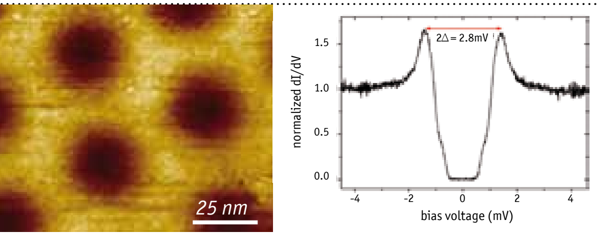
LabVIEW™ control

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

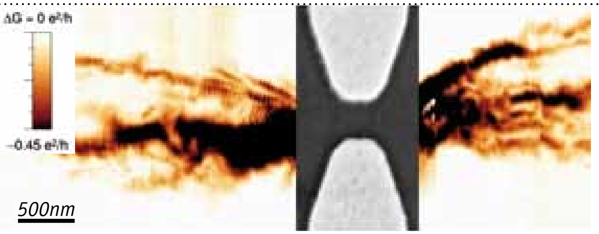
Spectroscopy

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.

07
ATTOCUBE SYSTEMS' MICROSCOPES
OPEN UP NEW POSSIBILITIES

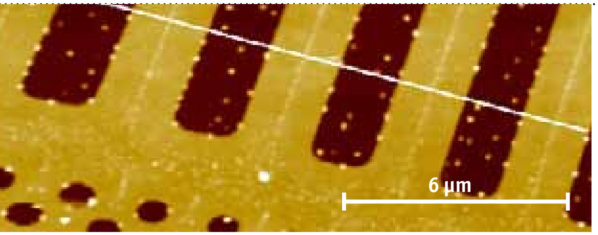


STS vortex imaging on $NbSe_2$ at 315 mK and 1 T external field. The image (left) was recorded at a bias voltage of 1.4 mV, corresponding to the superconducting coherence peak energy. The coherence peaks are suppressed inside the vortex cores, leading to the observed contrast. The image to the right shows a dI/dV spectrum of $NbSe_2$ revealing a local superconducting gap with 2Δ equal to 2.8 meV (attocube application labs, 2009).



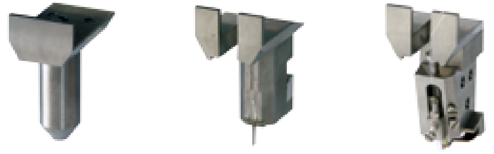
Characteristic branched-flow of electrons at zero magnetic field showing electron interference fringes and the actual electron path. T = 400 mK, 2DEG density $n_{2D} = 3.37 \times 10^{11}$ cm^{-2}.

The data were generously provided by S. Heun et. al., NEST, CNR-INFM and Scuola Normale Superiore, Pisa, Italy.



AFM contact mode image of a Si-substrate/SiO_2-layer. Height: 20 ± 2 nm recorded at 10 K using a closed cycle pulse tube cooler. The images were recorded with the cooler on (attocube application labs, 2007).

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.

08
ATTOCUBE SYSTEMS
CREATING SCIENTIFIC IMPACT

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