Design and performance of a beetle-type double-tip scanning tunneling microscope

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(Received 23 May 2006; accepted 28 June 2006; published online 12 September 2006; publisher error corrected 22 September 2006)

A combination of a double-tip scanning tunneling microscope with a scanning electron microscope in ultrahigh vacuum environment is presented. The compact beetle-type design made it possible to integrate two independently driven scanning tunneling microscopes in a small space. Moreover, an additional level for coarse movement allows the decoupling of the translation and approach of the tunneling tip. The position of the two tips can be controlled from the millimeter scale down to 50 nm with the help of an add-on electron microscope. The instrument is capable of atomic resolution imaging with each tip. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2336112]

I. INTRODUCTION

A current challenge in nanoscience is to measure the charge transport through nanostructures grown by self-assembly. The controlled fabrication of such self-organized nanostructures with dimensions in the single digit nanometer range has become possible. For instance, semiconductor nanowires and nanorings with a width down to a few atoms have been fabricated in a controlled way.[1,2] Quantum effects are expected in the charge transport through self-organized nanostructures.[3] Besides the fabrication aspects, the ability to provide contacts to the nanostructures in order to characterize them is a major challenge, since, in contrast to nanostructures grown by lithographic methods, the location of the self-organized structures is not predefined. The scanning tunneling microscope (STM) is an appropriate tool for imaging these nanostructures down to the atomic range and for characterizing them by spectroscopic methods.[4–6] However, only one probe alone is not sufficient to measure the charge transport properties of laterally grown nanostructures. An additional probe is needed to provide the second contact.

Several approaches have been demonstrated to integrate a multitip STM with up to four probes in ultrahigh vacuum (UHV) environment.[7–10] It turned out that the controlled positioning of the tunneling tips close to each other is one of the main difficulties.[10] The solution for a fast and well-defined approach of the tips is to use an add-on scanning electron microscope (SEM) that allows imaging over a broader range of resolution than provided by the STM.[11] In Fig. 1 the double-tip STM can be seen imaged with the add-on SEM column. Besides the high-resolution imaging capability, the SEM can also give a larger overview of the assembly.

Another difficulty is achieving high mechanical stability on the two tunneling junctions. This is important to obtain atomic resolution with each tip. Atomic resolution is a benchmark criterion for a low noise level, which is required for spectroscopic charge transport measurements. Therefore, it is essential to make the whole construction as small and rigid as possible. In this article we describe a construction based on the Besocke beetle-type STM.[12,13] This type of STM shows unique properties in rigidity, thermal drift compensation, and simplicity of use. In particular, the possibility of integrating the main components (coarse approach, coarse movement, sample holder, and scanner) in a small space makes this concept promising for a double-tip STM.

II. INSTRUMENTAL DESCRIPTION

The original beetle-type STM consists of a ramp ring, which is supported by three outer tube piezos. The ramp ring is divided into three helical sectors. Due to the rotating motion of the ramp ring, the distance between sample and tunneling tip can be adjusted. This rotation is realized by applying sawtooth voltage pulses to the outer three piezos. Thus slip-stick motion of the ramp ring is induced and the ramp ring can be moved vertically (in z direction) by performing an up or down rotation. Lateral motion is realized by performing a slip-stick motion of the ramp ring in the xy direction.

One drawback of this scheme of coarse movement is that the tip-sample distance is also slightly changed by moving the ramp laterally. For STM measurements on homogeneous surfaces, this is not a problem because the tip can be approached anywhere. However, for contacting nanostructures it is advantageous to be able to guide the tip over the surface without changing the height.

Because of this coupling between vertical and lateral movements in the original beetle scheme, we introduced a second ring which is exclusively devoted to transversal movement (Fig. 2). Since this flat ring is planar, any motion of the flat ring will not affect the tip-sample distance. Hence, the vertical and lateral motions are decoupled by using these two rings. The flat ring and the ramp ring are stacked on top of each other as shown in Fig. 2. The scanning tube piezo, which provides the fine movement of the STM tip, is mounted to the upper ramp ring, so that it performs both motions: the lateral motion of the flat ring and the vertical

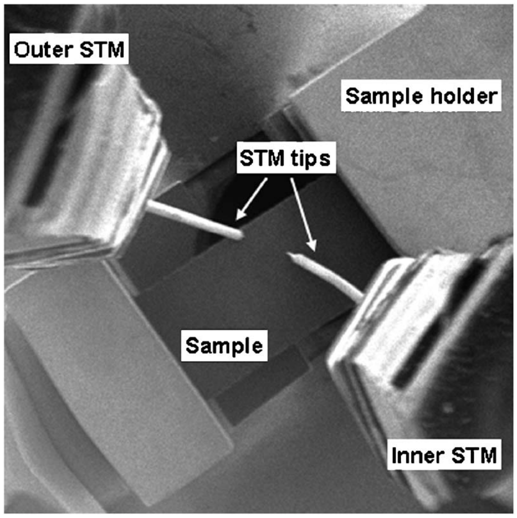

FIG. 1. Low magnification SEM image of the sample stage. It shows the sample in the center and the free movable STM scanners in the upper left and lower right. The large scan area of several millimeters leads to a distortion of the image. The width of the sample is ~3 mm.

motion of the ramp ring. The rotation of the ramp ring, which now rests on the flat ring, can be compensated for by rotating the flat ring in the opposite direction. Therefore, it is possible to approach the tip to the sample without changing its position. The flat ring itself is supported by a rigid tripod made of stainless steel. The additional flat ring needs another three piezoelectric elements. This makes six piezo elements altogether for coarse movement of one tip. To retain the compactness of the original beetle STM, the outer tube piezos were replaced by smaller shear piezo elements.[14] To move the flat ring, shear piezo elements with a size of $3 \times 3 \times 5$ mm^3 (PI Ceramic GmbH) and two active axes for the x and y directions were used. Shorter shear piezos with a size of $3 \times 3 \times 3.5$ mm^3 and only one active axis can move the ramp ring. Small magnets are glued onto the shear piezos for a stronger connection of the rings to each other and to the tripod.[15]

A second pair consisting of a ramp ring and a flat ring with a larger diameter is needed to introduce the second STM tip. This pair is aligned coaxially above the first pair and sits on the same tripod (Fig. 3). Each pair of rings is equipped with a central clearance to give the scanner piezos and the electron beam enough freedom of movement. The

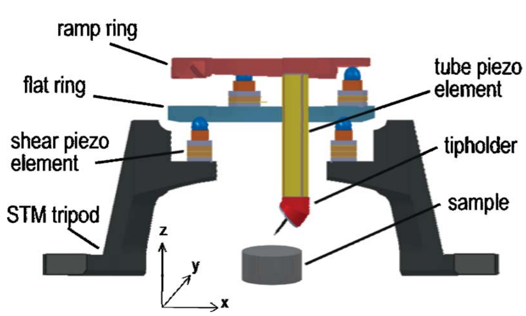

FIG. 2. (Color online) A sectional view of the inner STM stage. The flat ring for coarse translational movement rests on a rigid tripod. The ramp ring with the attached tube piezo scanner is mounted on the flat ring. Slip-stick motion is induced by shear stack piezoelectric actuators.

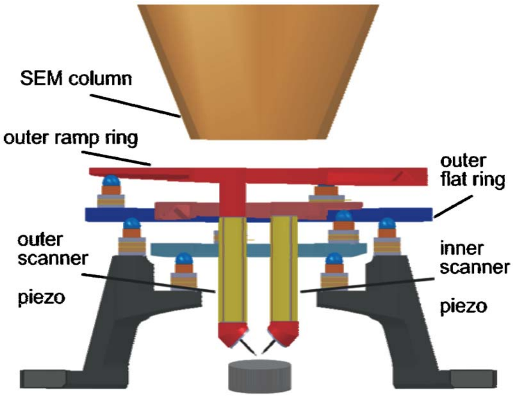

FIG. 3. (Color online) A sectional view of the double-tip STM including inner and outer STM stages. The electron focusing column (FEI Beam Technology) is aligned coaxially to the double-tip STM and has a distance from the sample of ~25 mm.

tunneling tips have an angle of 45° with respect to the surface of the sample, which is located below the scanners.

A SEM is used to monitor the alignment of the two probe tips close to each other and to the surface of the sample. The SEM (FEI Beam Technology) utilizes Schottky emission and electrostatic focusing optics to provide a resolution of ~50 nm at 25 mm working distance and 25 kV accelerating voltage. Under these conditions, a raster size of 2×2 mm^2 with maximum deflection voltage is possible. A detailed description of the SEM assembly is given elsewhere.[16] To align structures on the sample and the two STM tips relative to the axis of the SEM, the STM stage, including the STM tripod and the sample holder, can be moved by three stacks of shear piezos using the slip-stick motion.

The double-tip STM and the SEM column are attached to an UHV system consisting of a preparation chamber and an analysis chamber. The preparation chamber accommodates several sample treatment facilities for cleaning and film growth. The base pressure in both chambers is $\sim 1 \times 10^{-10}$ mbar. The UHV system is decoupled from ground or building vibrations by four pneumatic legs (Newport Corporation).

The double-tip STM is mounted on a secondary spring suspension stage, which decouples the double-tip STM from vibrations of the UHV chamber. This suspension is made of standard tension springs and eddy current damping permits high-resolution STM operation. However, in order to obtain well-resolved SEM images of the STM, the STM cannot be decoupled from the chamber since a rigid connection between the SEM column and the STM is needed. For this reason the STM stage can be fixed to the STM/SEM chamber by pressing it against rigid clamps. However, even without the secondary spring suspension, it is possible to obtain atomically resolved images due to the compact and rigid design of the double-tip STM.

III. INSTRUMENT PERFORMANCE

A. SEM observation

As seen in other previous attempts[8,10] for a fast and precise aligning of the tips, it is necessary to make use of a

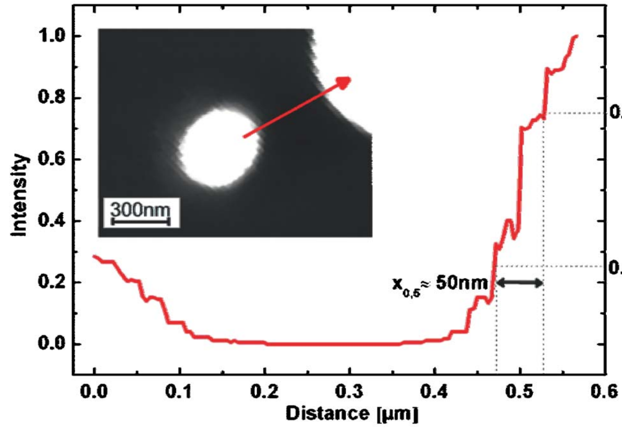

FIG. 4. (Color online) The graph shows a line profile of the SEM image along the arrow line marked in the inset. The SEM image shown as the inset was taken with the highest magnification and it displays two dust particles on a silicon surface. The rise distance $x_{0.5}$ is a measure of the edge resolution.

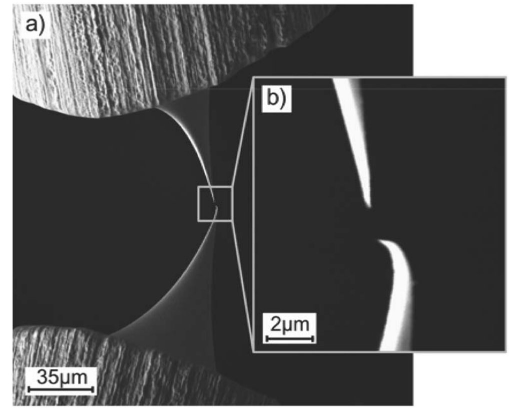

FIG. 5. SEM images of two STM tips on a silicon surface. (a) Lower magnification scan showing the electrochemically etched tungsten tips. (b) Closer view of the tips with higher magnification. The distance between the two tips is ~1.5 μm. The lower tip is bent due to a previous sample contact.

microscope that resolves tens of nanometers in a field of view of several millimeters. The tips first have to be localized in a larger area and then they have to be brought close together to a point of interest at the sample surface. The add-on electron column used in this instrumentation satisfies these requirements.

Small dust particles on a silicon sample were scanned to evaluate the SEM performance. The edge resolution can be defined as the rise distance $x_{0.5}$ between the points corresponding to 25% and 75% of the detector signal intensity.[17] From the line profile in Fig. 4 the edge resolution can be estimated to be 50 nm. This shows that the add-on electron column is capable of guiding the STM tips towards nanostructures as small as 50 nm.

To find much smaller structures the ultimate resolution of the STM has to be used. However, in this case as well, with the help of the SEM, the tips of the double-tip STM have to be brought close together. Only if the structures of interest are within the scan range of both STM tips can they be reached and investigated with both tips at the same time. The maximum scan range of the scanning piezo tube is usually defined by the lateral piezo constant and the maximum voltage applied to the piezo. In the present case, the scan range is also limited by another effect. The STM tips are inclined by 45° relative to the piezo scanner. Hence, the apex of the STM tip is not on the axis of the piezo tube scanner. Therefore, a lateral deflection of the scanner tube in the direction of the tip apex will lead to a noticeable change of the tip-sample distance.[8] For the given geometry of the double-tip STM, this effect causes a virtual sample tilt of ~20° while scanning the tip over the surface. To keep the tip-sample distance constant, the lateral deflection of the piezo tube has to be compensated for by a certain length extension of the piezo tube. Thus, the scan range is also limited by the maximum vertical extension of the scanning piezo. In the present case the maximum range is confined to $4 \times 4\ \mu\text{m}^2$. Hence, the tip-tip distance has to be in the micrometer range or smaller to achieve an intersection of the scan range of both STM tips.

In Fig. 5, the two STM tips were brought close together using slip-stick movement of the shear piezo elements (Fig. 2), while monitoring the tip positions with the SEM. The remaining distance of ~1.5 μm is sufficient to image the same structures with both STM tips. The tips can be approached closer to each other using the central tube piezo scanners.

The minimum practical lateral separation of both STM tips in tunnel contact is limited by the radius of curvature of the tip apex. With chemically etched tungsten tips, a radius of curvature of ~50 nm can be obtained. This would lead to a minimum tip-tip distance of 100 nm.

B. STM overlap

In Fig. 6 two constant current images obtained with both STM tips are presented. The images show the overlapping area on a silicon (111) surface. The area was first scanned with the inner STM and after parking the tip at a safe distance, the outer STM tip was used to image the same region.

To demonstrate that it is the very same area, four identical objects in the images are highlighted by circles. Besides some small terraces, the most evident feature are two scratches in the lower left of both images. The difference in the step orientation of the two images originates in the different orientation of the inner and outer STM. In addition, piezo creep leads to a different distortion of the images.

This result shows that the double-tip STM is able to image the same objects of nanometer size with both STM tips. This ability will be essential for contacting and electrically characterizing nanostructures.

C. Atomic resolution

To image and study nanostructures consisting of only a few atoms, which are most promising for quantum electronics, atomic resolution is indispensable for the instrument. Therefore atomic resolution is the most desirable, but also the most delicate feature of a multitip STM. If single atoms can be resolved, the position of the tip with respect to the surface is very stable. This is particularly important for spectroscopic measurement with the STM. To demonstrate the

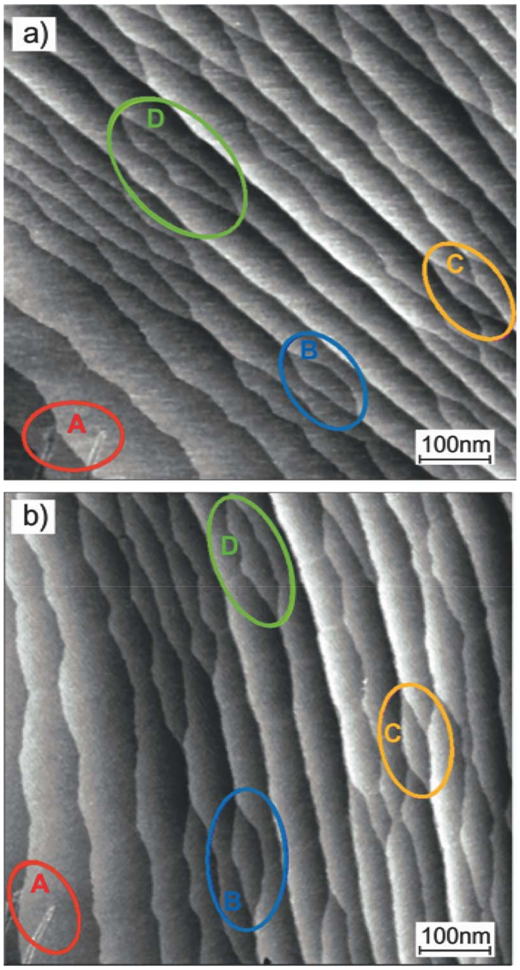

FIG. 6. (Color online) STM images of an overlapping scan area taken with the two tips of the double-tip STM. (a) STM image of 3.1 Å high atomic steps on silicon (111) surface obtained with the inner STM. Specific objects such as scratches and small terraces are marked by circles. These objects were also imaged with the outer STM (b). The scan range of both images is $\sim 1\ \mu$m.

ability of the beetle-type double-tip STM to resolve single atoms, the prominent (7×7) reconstruction of the silicon (111) surface was chosen. In Fig. 7, a constant-current-mode scan with positive sample voltage is presented. The adatoms of the (7×7) unit cell can be clearly recognized. This measurement was performed with the inner STM. However, the outer STM has nearly the same attributes and is capable of atomic resolution as well.

IV. SUMMARY

In summary, we have presented a new concept of a multiprobe STM. By using the reliable beetle-type design, two STM stages were arranged coaxially. Furthermore, the original Besocke design was extended by an additional flat ring to provide the probes with full freedom of movement. In order to reduce the size of the instrument, small shear piezoelectric elements were used. An add-on SEM provides safe navigation of the two STM tips down to the nanometer scale. The instrument shows all the features which make it a promising tool for measuring charge transport through nanostructures. A patent for this new concept of a multiprobe STM is

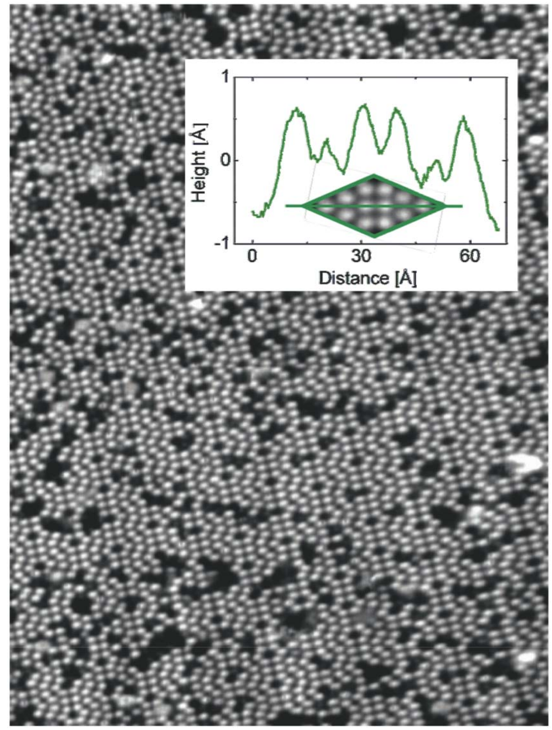

FIG. 7. (Color online) The double-tip STM exhibits atomic resolution with each tip. The image shows the silicon $(111)-7\times7$ surface reconstruction. The inset displays a closer view of the (7×7) unit cell and a corresponding line scan.

pending.[18] It is straightforward to extend the concept of the described beetle-type double-tip STM towards a four-tip STM with the ability to perform four-point probe measurements on the nanoscale.

ACKNOWLEDGMENTS

The authors would like to thank the machine shop of IBN for the outstanding precision engineering of all parts of the instrument. Thanks are also due to Joseph Myslivecek, Helmut Stollwerk, and Udo Linke for helpful support.

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