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AN EASILY OPERABLE SCANNING TUNNELING MICROSCOPE

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A new type of scanning tunneling microscope (STM) has been developed by the combination of several equivalent x-y-z piezoelements into one compact operation unit. Surface scanning as well as sample manipulation can be carried out simultaneously and independently in any desired direction. High stability operation is achieved by temperature compensation and rigid construction in order to reduce the influence of drift and vibration. Low voltage operation, easy sample mounting and free access for other surface analysis tools render the application possible also for normally skilled users.

1. Introduction

With the invention of scanning tunneling microscopy (STM) by Binnig and Rohrer [1] a new window was opened to a fascinating view on the atomistic world of real surfaces. The chances of looking at individual atomic or molecular microstructures triggered a vivid activity all over the world and the field of applications is expanding dramatically [2–11]. One of the advantages of the STM is that it can be operated in air, gases or liquids. It does not require the environment vacuum used in most high resolution microscopes and surface analysis tools. Samples, organic molecules or biological structures can now be analyzed in their natural surroundings thus leading to a more realistic view of nature.

The direct view at atomic microstructures without using statistical or diffraction methods implies, however, a great effort for stabilization. Local displacements between specimen and sensing tunnel tip caused by vibration and thermal drift have to be kept much smaller than the object under investigation. In the past few years many successful attempts were made to improve the stability and performance of the STM. Vibration reduction was achieved by using highly efficient damping stages and by developing rigid constructions [8,12,13]. Thermal drift problems were reduced with compensation methods [14]. These provisions lead, however, to constraints which are at variance with the need for easy sample handling and free sample manipulation.

The intention of this paper is the demonstration of a new type of STM which combines high stability, free sample handling and manipulation and which can be operated routinely by normally skilled users.

2. Description

The development of the STM presented here has been guided by two major demands which we tried to obey without any compromise. The demands are stability and simplicity. These are not contradictory: they are important factors preventing uncontrollable relative movements between specimen and tip. The stability demands were relatively easy to fulfill by using rigid construction elements with eigenresonances for all components, far above ground vibration- and microphonic frequencies in order to avoid energy coupling with the environment. Temperature compensation measures were also applied in order to reduce thermal drift. All main elements of the STM (base plate, scanner, sample holder and sample manipulator, tip, sample) had to be condensed to a rigid unit in order to reduce uncontrollable relative movements between tip and specimen to a minimum. Once the tunnel gap has been stabilized, the damping of the whole system itself is only of second-order importance and can be accomplished e.g. by using conventional stack arrangement [16].

To fulfill the demand for simplicity turned out to be much more complicated. The only practical way to achieve this was by consequent reduction of parts, materials, constructive elements, joints and, last but not least, the reduction of all dimensions.

The importance of the reduction principle becomes apparent by considering the one-dimensional schematical block diagram of a conventional STM used so far, fig. 1. The gap between sample and tip of the order of ångströms has to be stabilized by a combination of various construction elements with dimensions in the centimeter range. This extreme mismatch of more than 8 orders of magnitude is the main problem to overcome, since all these construction elements like base plate, sample manipulator, sample holder, sample, tip and scanner unit are affected by vibrations and thermal drift. Improvements are only possible by getting rid of as many construction elements as possible and by the reduction of all dimensions, i.e.: minimization of the effective operation volume of the STM.

As a final result of this simplification concept a rigid STM with an effective operation volume of less than 0.5 cm^3 came up, consisting of only three major construction elements: the base plate, the piezoelectric elements and the sample.

The principle of operation of the new STM design is shown schematically in fig. 2. The base plate – a rigid metal plate – holds four identical

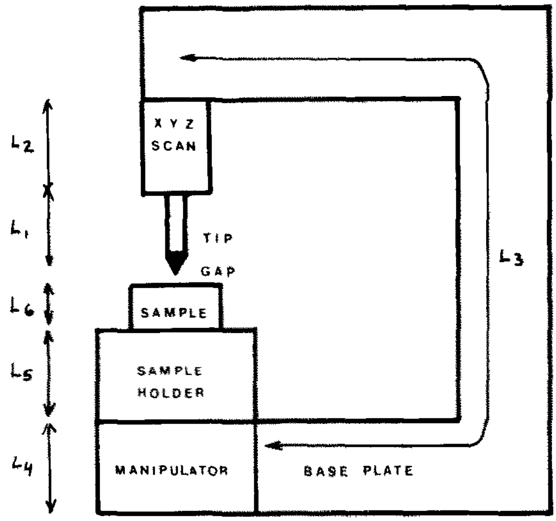

Fig. 1. Schematic block diagram of a conventional STM elucidating the demand for reduction of components and dimensions. ΣL_n is of the order of cm; the gap is of the order of Å.

piezoelectric tube elements. On one side, the piezoelements are bonded tightly to the base plate whereas their other ends are free for action and can be actuated in x, y and z direction by applying appropriate electric signals. The three outer piezoelements arranged in a triangle configuration are acting as sample carriers. The fourth piezoelement located inside the three carriers acts

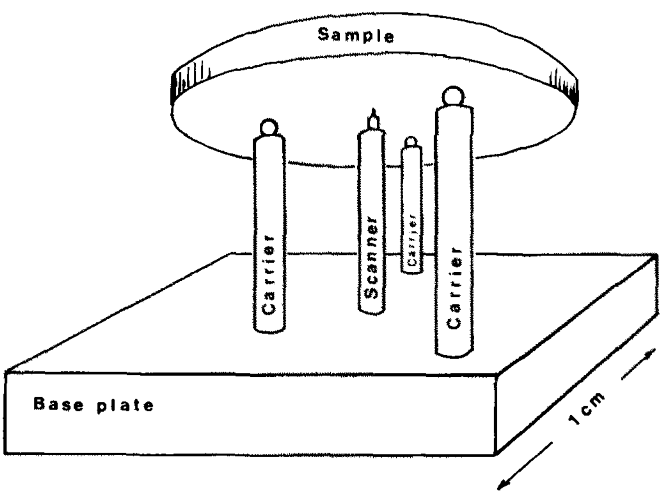

Fig. 2. Schematic principle of operation of the new STM design.

as a scanner. The free ends of the carriers are equipped with small metal spheres (1.5 mm ball bearing spheres) on which the sample is laid down. The sample rests stable on these three points. It is kept down only by gravity, no sample holder being normally required. In case of nonhorizontal operation the sample can be pressed to the carrier spheres using a small spring. Since the sample surface under investigation rests on the spheres, no special sample shaping regarding thickness, size or shape is required. The electric connection of the sample is provided via the metal spheres. The scanner holds the tunnel tip at its free end.

Since all four piezoelectric elements are identical in size and function it is obvious that this STM system in itself is completely temperature compensated.

As piezoelectric elements, tubes of piezoceramic material were used. The advantage with respect to the conventional orthogonal x-y-z tripod arrangement is that all needed movements can be carried out by only one tube which is small and more rigid than the combination of three different slabs. A second advantage is the low operation voltage. For normal operation, standard electronics with supply voltages of ± 15 V are sufficient. The principle of operation is demonstrated in fig. 3 for the piezoelectric scanner element holding the tunnel tip on the free end. However, the three sample carrier elements are acting identically. The tubes are 10 mm long with an inner diameter of 1 mm and an outer diameter of 2 mm. They are polarized in radial direction and provided with one metal electrode covering the inner wall of the tube and four sections of electrodes on the outside of the tube. The tube is

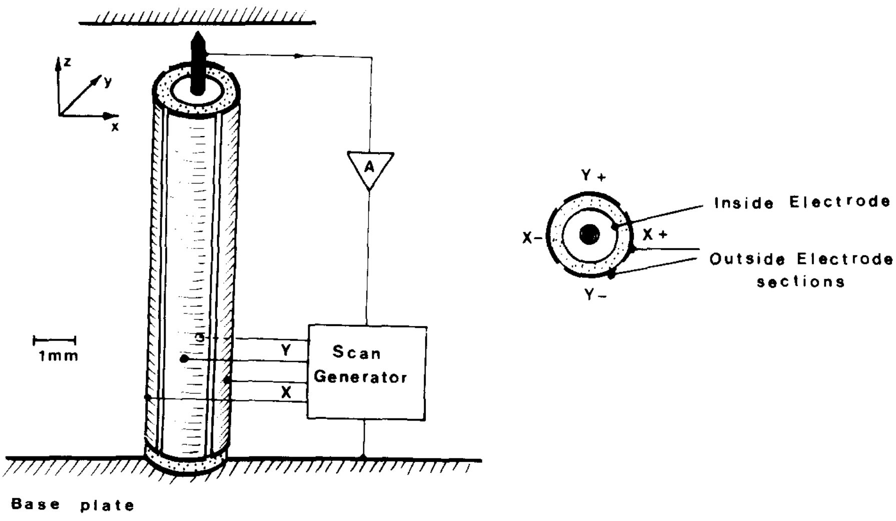

Fig. 3. Function diagram of piezoelectric actuator element equipped with tip and electronic connections for scanner operation. The carrier elements are identical in size and function.

stretched or shrinked by applying a positive or negative voltage between the interconnected outer electrode sections and the inner electrode thus providing the motion of the tip in z direction. Motion of the tip in x or y direction is carried out by applying an antisymmetric voltage between diametral section pairs of the outer electrodes and the inner electrode. By vectorial addition of the voltages for x and y motion, the sample surface can be scanned in any desired direction. Fig. 3 includes schematically the electronics for the STM operation. A scan generator is connected to the four outside electrodes of the piezoelement. The inner electrode is normally grounded. Scan speed, amplitude and scan direction are variable. The tunnel current is picked up from the tip, amplified, integrated, superimposed to the scan generator and fed back to the z drive of the piezoelement using the conventional method.

The speed of operation is limited by the eigenresonances of the piezoelement. Resonance frequencies of about 100 kHz for the stretching mode and 10 kHz for the bending mode were measured. These high resonance frequencies allow for high scan speeds. Scan images can be obtained in less than 1 s. The piezoelectric conversion factor of the used piezoelements was calibrated with a Sloan Dectac II surface profiling instrument. For the stretching direction (z) 24 Å/V and for the bending direction (x, y) 80 Å/V was determined. Operating with voltages of ± 15 V, scan areas of up to 2400 Å times 2400 Å are covered. In z direction amplitudes of ± 360 Å can be reached. If necessary, these values can be increased by more than a factor of ten by using higher operation voltages. The piezotubes allow operation voltages of up to ± 250 V.

For sample manipulation purposes the three sample carrier piezoelements have to be actuated simultaneously. The function of these elements is identical to that of the scanner element. By synchronous electronic control of the three carrier elements, the sample can be lifted or moved in any desired direction.

Fine adjustment of the distance between specimen and tip is accomplished by applying a variable DC voltage to the z-electrodes of the carrier elements. A range of more than 10000 Å can be covered by applying voltages between ± 250 V. For the initial coarse distance adjustment, one of the three carrier elements can be lifted or lowered mechanically with a suited micrometer screw or lever construction in order to bring the tip distance into the action range of the piezoelements. Once the distance between tip and sample has been adjusted coarsely, the STM will accept any sample without readjustment, as long as the sample surfaces are flat within the z variability range of the carrier and scanner piezoelements. In the current construction samples with deviations up to ± 1.5 μm over a width of 1 cm can be measured without the need of a coarse mechanical readjustment.

For contact potential studies the distance between specimen and tip has to be modulated. This can be accomplished by superimposing a small AC component to the z DC voltage of the carrier piezos.

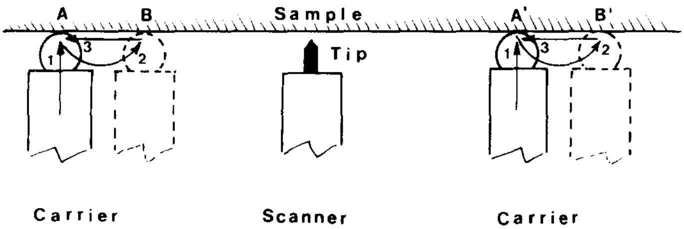

Fig. 4. Principle of piezoelectric sample manipulation over macroscopic distances.

The carrier piezoelements are acting not only as sample holder and distance adjuster; actuating the x and y component of the three carriers simultaneously causes the sample to shift. The displacement is determined by the piezoelectric conversion factor of 80 Å/V.

By vectorial addition of the x and y component and by variation of the voltage, the sample can be moved in any desired direction within the bending range of the piezoelements.

Movements of the sample over macroscopic distances can be carried out by suited voltage pulses synchronous applied to all three carrier piezos. Fig. 4 shows the principle of operation. The upper section of the STM is shown with the free ends of two carrier elements supporting the sample and the scanning piezo with the tip in between. The applied voltage pulses to the x-, y-, z-electrode of the carriers are programmed in a manner to cause a movement of the free ends as indicated by the arrows: in a first step (1) the sample is lifted up in order to increase the distance to the tip. In a second fast acting step (2) the carrier piezos are lowered, moved to the side and lifted up again. If this movement is fast enough the sample will not be able to follow this action and will stay in place due to its inertness. As a consequence the sample will be supported at the end of step 2 at a different point B. In a third step the carrier piezos are moved slowly back to the starting position A, carrying the sample the distance A–B. This voltage function can be applied as a single pulse or in a sequence causing a pseudo-continuous movement of the sample. Step length, movement, velocity and direction can be varied over a wide range. The method proved to operate on silicon wafers as well as on metal or graphite samples with polished and rough ground or etched surfaces. Reproducible single steps ranging from 50 to 1000 Å were measured by evaluating the shift in the obtained STM pictures. The movement velocity was measured with an optical microscope. Depending on step length and repetition rate, speeds up to 33 μm/s were obtained.

The preliminary results with this STM design are quire promising. The STM was taken into operation in air atmosphere, placed on a normal laboratory bench in the second floor of the lab building. A three-stage stack of

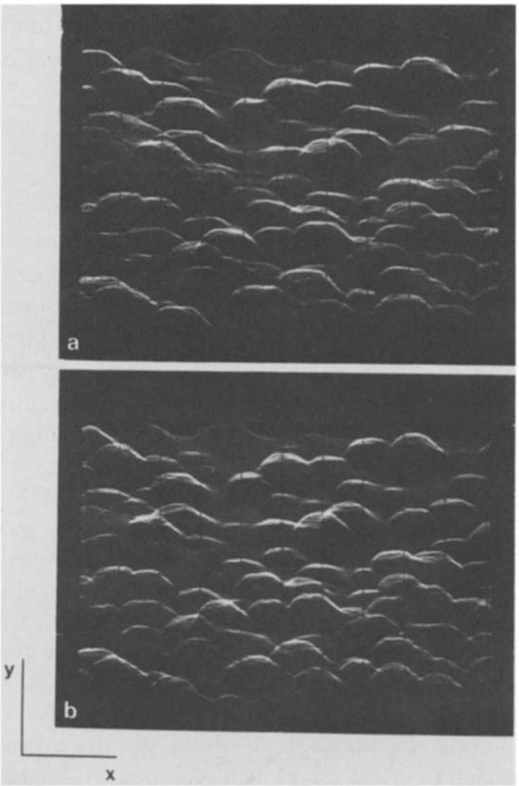

Fig. 5. STM image of an Au covered Si(111) surface. Scan B was taken 15 min after scan A for stability- and drift test. Scan time 5 s/frame. Deflection: x, y: 100 Å/div; z: 10 Å/div, superimposed on y.

metal plates insulated with viton pellets as described in literature [16] was used for damping of ground vibrations. No special precautions were taken to prevent microphonic coupling. The electric connections (except the tip connection) were unshielded and not attached to the damping stages. The room temperature was not stabilized. Changes of up to 6°C were measured during the work hours. The thermal drift as measured by comparison of pictures of the same object taken at different times was less than 2 Å/min. This value is certainly tolerable in relation to the scan time of only a few seconds. Fig. 5 shows STM pictures of a Si(111) surface on which a Au layer about 50 Å thick was deposited by sputtering. The pictures A and B were taken from the same object at a time interval of 15 min in order to demonstrate reproducibility and thermal drift effects. The scan sensitivity was 100 Å/div in x and y direction and 10 Å/div in z direction. The scanning time was 5 s. The pictures show the typical conglomeration of gold atoms into clusters of about 100 Å in diameter.

Atomic resolution was recently achieved on a graphite test sample. Similar pictures as reported by Hansma and Quate and co-workers [15,9] were obtained.

3. Conclusion

A new concept of STM construction was taken into operation. The STM consists of only three major components (base plate, four identical piezoelectric elements and specimen) which are confined in an effective operation volume of less than 0.5 cm^3. The microscope features are: simple operation, easy sample handling, free sample manipulation in all directions, atomic resolution, fast scanning rates, low voltage operation and high stability due to a rigid, temperature compensated construction.

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