Compact coarse approach mechanism for scanning tunneling microscope

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We report on the design and fabrication of a coarse approach mechanism, called a piezotube walker, based on a piezoelectric tube moving inside a triangular prism shaped cavity. This walker walks like a six legged insect moving its legs one by one and then the belly following. The walker works in any orientation from horizontal to vertical and its motion is found to be linear with the applied voltage above a threshold voltage. A compact scanning tunneling microscope (STM) was fabricated using this approach mechanism. The scanner tube of the STM is mounted on the inside of the walker tube, reducing the size of the STM considerably. Topographical images with atomic resolution were obtained for layered materials like graphite and $NbSe_2$. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1394181]

I. INTRODUCTION

Ever since its discovery by Binnig and Rohrer,[1] scanning tunneling microscope (STM) has been proven to be an excellent instrument for studying the conducting surfaces and their electronic properties. It has been successfully used for a wide variety of materials from simple metals to exotic materials like superconductors, charge-density waves, etc. Since a STM operates at subnanometer level distances, its mechanical design plays a very crucial role in its performance in terms of sensitivity, rigidity, and noise. One important part of the STM that affects its design and performance extensively is the coarse approach mechanism.[2] This mechanism is needed to bring the tip and the sample surface within the range of the scanner piezo ($<1\ \mu$m), starting from a separation of about a few millimeters. Therefore, the purpose of this piezotube walker is to provide the needed long-range motion with submicrometer resolution. The sensitivity of a STM to the mechanical noise is determined by its compactness and rigidity. This puts severe constraints on the design of the coarse approach mechanism.

A number of coarse approach mechanisms have been used in the past. One common technique is to deform the piezoelectric actuators periodically to provide a one-dimensional motion. This has been implemented in several different ways. In a technique called inertial approach mechanism,[3] a carrier is moved on a pair of rails by shaking the rails back and forth with asymmetric accelerations. Although this technique is restricted to work in horizontal plane only, it has been used widely because of its simplicity. Variants of this method have been developed, but they are not as simple and versatile. An example is the electrostatic louse, used by Binnig *et al.*,[4] however, it is restricted to horizontal motions only and it makes the STM quite bulky. Some recent variations include the use of magnetic clamping[5] or mechanical spring force[6] to create friction and to hold the carrier on vertical surfaces. Inchworm®[7] can work in any orientation but it is expensive and it does not reduce the STM size very much. A mechanism, called "piezoelectric motor," was developed recently by Pan based on a sapphire prism being pushed by six stacks of shear mode piezoelectric plates.[8] We have developed an approach mechanism based on a similar principle but implemented in a simpler and less expensive way. Our piezotube walker uses a piezoelectric tube, which crawls on the inside of a triangular prism shaped cavity. This approach mechanism can be used in any orientation from vertical to horizontal and it makes the STM much smaller in size as the scanner piezotube can be accommodated inside the walker tube.

II. DESCRIPTION

A piezoelectric tube with the specifications given in Table I was used to make the piezotube walker. Six identical 8.9 mm long sections (three at each end) were cut along the axis of this tube as shown in Fig. 1. In this way the tube has three parts, the two ends that are sectioned and the central connected part. Each of these sections can be independently expanded or contracted by applying a voltage between the inner and outer electrodes after separating the nickel electrodes. However, to simplify the electronics, the electrodes were arranged as described in the next paragraph. The electrical and mechanical parameters for each of these sections are given in Table II. A circular sapphire disk of 5 mm diameter and 0.5 mm thickness was attached using TorrSeal®[9] epoxy at the end of each of these six sections as shown in Fig. 1.

The outer nickel electrodes of the left-end sections were separated from rest of the inner electrode of the tube. Similarly, inner electrodes of the right-end sections were separated from the rest of the outer electrode of the tube. This separation of electrodes is shown in Fig. 1. After this separation, the inner electrodes of left-end sections are still connected to that of the central part of the tube and similarly, the outer electrodes of the right-end sections are connected to that of the central part of the tube forming two big electrodes on the inside and outside of the tube. These two electrodes are connected to each other using a copper wire, which in

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TABLE I. Specifications of the walker tube.

Material:	PZT-5H
Diameter, d:	12.5 mm
Thickness, t:	1.0 mm
Length, L:	2.5 mm
d_{31}	-2.74×10^{-10} m/V
Y	6.1×10^{10} N/m^2

TABLE II. Physical parameters for a cut section of the walker tube.

Section length, l:	8.9 mm
Cross-section area, A:	12.4×10^{-6} m^2
Spring constant, $C_1(=YA/l)$:	8.5×10^7 N/m
$D(=d_{31}l/t)$	2.4×10^{-9} m/V
$E(=C_1D)$:	0.2 N/V

turn forms the ground lead for the voltage applied on the other six electrodes. In this way, one end section can be expanded while the other end section can be contracted or vice versa for the same polarity of the applied voltage relative to the ground while the central part remains unchanged.

This tube was fit inside a stainless steel triangular prism shaped cavity with polished internal surfaces as shown in Fig. 2. The numbers in parentheses in the text refer to those in Fig. 2. This cavity is made of two pieces, the bottom V-shaped part (5) and the top plate (2), forming a triangle. The bottom part (5) is further composed of two identical pieces, which are rigidly put together using two screws (not shown in Fig. 2). This is done to access the two surfaces for polishing. The top plate and the bottom V-shaped pieces comprising the cavity are put together using two sets of steel springs (9,10) and a set of screws (1) in a differential configuration. The top spring (10) is stiffer than the bottom one (9). These springs help in controlling the force applied on the piezoelectric walker tube (8) and in aligning this tube inside the cavity. The force on the tube can be adjusted by tightening the screws (1); this in turn determines the frictional force on each of the sapphire disks. In this way the tube makes six contacts with the three surfaces of stainless steel cavity through the sapphire disks. The electrical connections to the tube are made using thin insulated copper wires. The other ends of these wires are connected to small circuit board posts anchored to the stainless steel body (cavity). These wires are coiled to allow some flexibility to accommodate the motion of the tube.

For the walker operation, it is important that three pairs of the sapphire prisms are parallel to the three faces of the cavity. To ensure this, the epoxy, to attach the disks to the tube, is applied after aligning the tube and the disks inside the cavity and putting the whole walker assembly together. After this step, to keep the alignment intact, the lower part of the cavity (which is made of two pieces) should not be dismantled and also the walker tube's orientation relative to the cavity should not be changed. The top plate can be removed, and has been removed several times, since the flexibility of the top plate due to springs ensures that the top plate stays aligned parallel to the top two sapphire disks. However, care must be taken in putting it back in terms of alignment and tightening the four screws equally. An unequal tightening of the screws can give rise to an asymmetry in the walker motion; however, this can be corrected by measuring the pushing force on the tube in both directions, backward and forward, using a force gauge and tightening or loosening the screws as necessary.

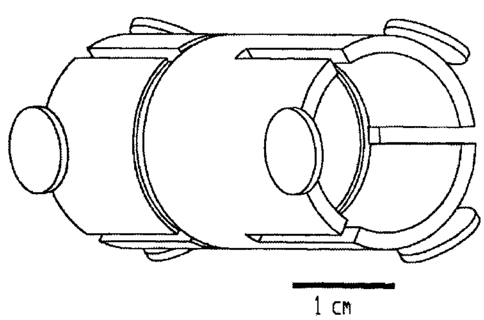

FIG. 1. Walker tube showing the sectioning of the two ends, sapphire disks and the arrangement of nickel electrodes. A 1 cm long bar at the bottom is included to show the scale.

III. OPERATION

An electronic circuit was specially constructed to operate this walker and has six synchronized voltage outputs. A voltage step is applied to each of the six sections of the tube, one by one, moving them along the same direction. Then the voltage on each leg is slowly brought down to zero at the same time (as shown in the inset of Fig. 3). This constitutes one step of the piezotube walker. The direction of motion can be controlled by the polarity of the applied voltage. The motion of this walker is similar to that of a six legged insect moving its legs one by one and then the belly following.

Suppose that a section of the walker tube has a cross-sectional area A, thickness t and length l, the spring constant

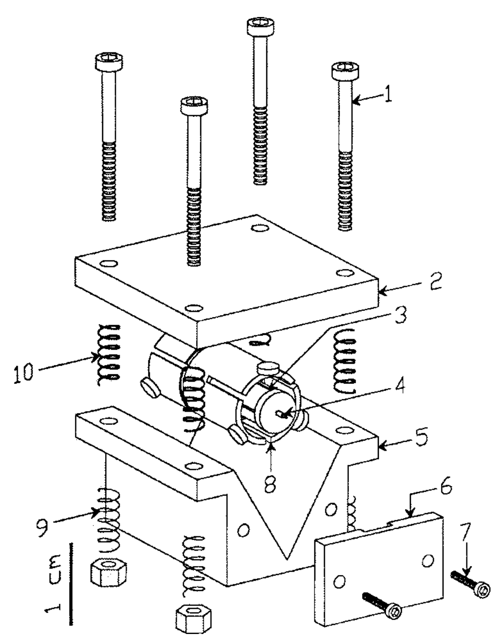

FIG. 2. STM assembly: (1) stainless steel screws to put the cavity together, (2) top stainless steel plate, (3) scanner tube, (4) tip holder, (5) stainless steel V-shaped cavity, (6) sample holder plate, (7) Teflon screws, (8) walker tube, (9), (10) springs. A 1 cm long vertical bar on the bottom left corner is included to show the scale.

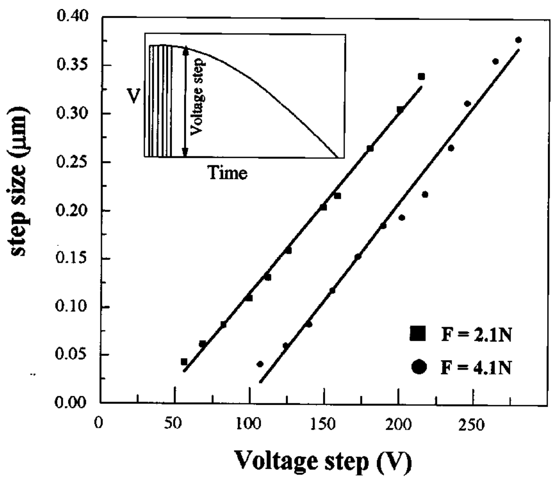

FIG. 3. Per step motion of piezotube walker as a function of the magnitude of the voltage step. The two lines are the linear best fits with the parameters given in Table III. The inset shows the voltage waveform used for the walker motion; six vertical lines show the voltage steps for six sections of the walker tube and the later part of the waveform is same for all the sections.

of the section will be given by, $C_1 = YA/l$, where Y is the Young's modulus of the tube material. If a voltage, V, is applied on an unrestrained section, it expands in length by $\Delta x = DV$, where $D = d_{31}l/t$. However, when a voltage is applied on a restrained section, as in the present configuration, it exerts a force on the sapphire disk given by, $f = EV$, where $E = C_1 D$. These parameters for the walker tube have been calculated as shown in Table II. If the force, f, exceeds the frictional force, the sapphire disk eventually moves by $\Delta x_e = D_e(V - V_t)$. Here D_e is effective D adjusted by the force constant of the rest of the tube and V_t is a friction dependent threshold voltage. The rest of the tube has a force constant $C = 5C_1 + C_2$, where C_2 is the force constant for the central part, which is $\sim 3.5C_1$ for the present geometry of the walker tube. Therefore,

$$D_e = D/(1 + C_1/C) = 2.08\,\text{nm/V}, \tag{1}$$

hence, the motion per step (y) of this walker can be described by a linear relation:

$$y = D_e(V - V_t), \tag{2}$$

where the threshold voltage, V_t, can be written as $V_t = F_e/E$, with F_e as an effective friction force on each sapphire disk.

The walker was tested for its motion using an optical microscope. Although we tested it in horizontal as well as in vertical orientations, the results presented here were taken in horizontal position. The number of steps were counted for a known amount of displacement and thus the motion per step was calculated. As pointed out earlier the frictional force could be adjusted using screws 1 (Fig. 2), this force was measured using a force gauge by pushing the tube in the cavity. The voltage dependence of the motion per step is plotted in Fig. 3 for two different forces. The walker step size varies linearly with the voltage as expected. A numerical linear fit with Eq. (2) for the step size (y) vs voltage (V) for two different forces was made, the results of the fit are plotted in Fig. 3 and a summary of the fitting parameters is given in Table III.

TABLE III. Linear fitting parameters for the walker motion.

	$F = 2.1$ N	$F = 4.1$ N
$D_e(\times 10^9$ m/V)	1.87 ± 0.04	2.02 ± 0.08
V_t(V)	38.4 ± 2.3	97.3 ± 4.3
$F/6E$ (expected V_t)	1.8 V	3.4 V

The two values of D_e agree with each other and with the calculated value of 2.08×10^{-9} m/V [Eq. (1)] within error. From the measured value of F, the expected threshold voltage is $F/6E$, as listed in Table III; there is a surprisingly big disagreement here. The actual threshold voltage is more than a magnitude larger than the expected value. Pohl[3] attributed such large discrepancy in threshold voltage for his inertia walker to the deviations from the normal static friction limit when operating at such small-scale motions.

IV. STM

A STM was fabricated using this piezotube walker (see Fig. 2). The scanner tube (3) of the STM was mounted on the inside of this walker tube using a spacer. This is another advantage of this design in terms of further reducing the size of this STM. The tip holder (4) was made using a machineable ceramic (Macor®[10]) and it was mounted on the scanner tube holding the tip at the center. The preamplifier was mounted very close to the tip to minimize the noise pickup. The sample holder plate (8) was attached (but electrically isolated) to the stainless steel cavity using Teflon screws (7) as shown in Fig. 2. This STM is small enough to fit inside a cube of side 1.5 in. The STM was placed on a platform hanging from an air suspended vibration isolation table.

The electronics and the software used with this STM were from RHK Technology. The approach triggers in about 10 min if the starting distance between the sample and the tip

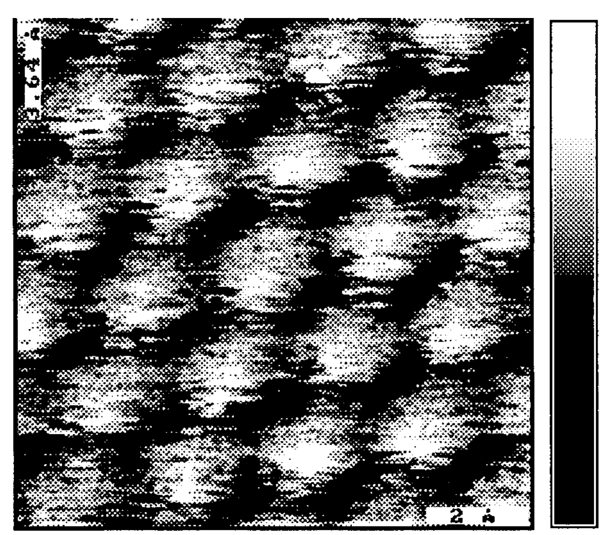

FIG. 4. Atomic resolution image of layered graphite in ambient conditions (60 mV bias, 1 nA tunneling current). The gray scale on the right-hand side corresponds to 0.36 nm.

is ~1 mm. Freshly cleaved graphite surface was imaged using an electrochemically etched Pt tip. A typical atomic resolution image of graphite in ambient is shown in Fig. 4. The scanner tube was calibrated for its *x*-*y* motion using this atomic resolution image. The calibration was then confirmed by atomic resolution images on $NbSe_2$.

In conclusion, we have successfully developed and tested a one-dimensional micrpositioner called piezotube walker. The walker has been tested in any orientation from horizontal to vertical. It has also been tested in vacuum (~2 Pa). We have used this walker to make a STM with atomic resolution image capability. With a more careful choice of materials, a more versatile STM can be designed for UHV, low temperature, and magnetic applications. Moreover, the walker is best suited, but not limited, for STM use; it can be used for any purpose where a few millimeters of motion is required with submicrometer resolution.

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[9] A product and trademark of Varian Vacuum Prod., Lexington, MA 02173.
[10] Macor® is the trade name of a machineable glass manufactured by Corning Inc., Corning, NY 14831-0001.