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NOTES

Compact design of a transmission electron microscope-scanning tunneling microscope holder with three-dimensional coarse motion

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A scanning tunneling microscope (STM) with a compact, three-dimensional, inertial slider design is presented. Inertial sliding of the STM tip, in three dimensions, enables coarse motion and scanning using only one piezoelectric tube. Using the same electronics both for scanning and inertial sliding, step lengths of less than 5% of the piezo range were achieved. The compact design, less than 1 cm^3 in volume, ensures a low mechanical noise level and enables us to fit the STM into the sample holder of a transmission electron microscope (TEM), while maintaining atomic scale resolution in both STM and TEM imaging. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1614872]

Transmission electron microscopy (TEM) and scanning tunneling microscopy (STM) are very powerful tools, both having the ability to image materials on the atomic scale. In addition, the STM has the very appealing ability to manipulate and alter the specimen on an atomic scale.[1] On the other hand, it is not possible to image the specimen during manipulation. Instead, the result has to be investigated afterwards. A combined instrument containing both a STM and a TEM would therefore be very desirable since it, for example, allows imaging during manipulation. The resolution of the TEM is strongly dependent on the size of the gap between the pole pieces of the objective lens. It is therefore not a trivial task to fit a STM inside the pole piece of a high resolution TEM. One way is to design a STM which is compact enough so that it can be fitted directly into a regular TEM side-entry holder, thus avoiding costly redesign of the TEM. The part that requires the most space in a regular STM is the coarse movement of either the sample or the tip. Inertial sliding motion[2] allows fairly compact designs, enabling coarse motion of either the sample[3,4] or the tip,[5–7] but three-dimensional coarse motion in particular is still rather voluminous.[8] Limiting the coarse motion to only one direction, i.e., the one to approach the tip to the sample, reduces the size and allows the use of fairly standard techniques such as, e.g., the inchworm,[9] micrometer screw,[10] or stepper motor.[11] However, this limits the accessible sample area to the scan range of the piezo, which is normally only a few μm in a high resolution STM, whereas the sample area of the TEM is much larger (a standard TEM sample grid has a diameter of 3 mm). Also, for TEM imaging, both the sample and the tip have to be very thin and positioned at exactly the same height, as opposed to reflection electron microscopy (REM) where the sample is thick.[9,12] Thereby coarse motion of the tip height inside the TEM is crucial in order to access the sample and hence coarse movement in at least two directions is necessary, while three directions are desirable in order to access the whole sample area.

Here we present an extremely compact STM design, with three-dimensional coarse motion, that can be fitted into a regular, side-entry, TEM holder. The compact design ensures vibrational isolation[13,14] and minimizes the need for external vibrational damping, thus retaining atomic scale resolution in both TEM and STM imaging modes.

Our design is based on a very compact, three-dimensional, inertial slider mechanism that holds the STM tip and is operated by the same piezo as the one used for scanning (see Fig. 1). The inertial sliding mechanism consists of a sapphire ball attached rigidly to the piezo tube and a movable part with six springs that embraces the sapphire ball. The movable part also holds the STM tip and will here on be referred to as the tip holder. A coarse motion step is achieved by applying a voltage pulse of either sawtooth or cycloid[15] shape to the piezo tube. The rapid movement of the sapphire ball during the voltage pulse cannot be followed by the tip holder and the springs will slide against the sapphire surface. Hence a ‘‘step’’ is taken in one of the three directions, depending on the direction of piezo movement. The motion of the tip apex will be the same as the motion of the tip holder for the direction parallel to the piezo axis, whereas in the other two directions the tip holder rotates around the sapphire ball and gives sideways translation to the tip apex. The magnitude of each step will depend on the shape and duration of the voltage pulse. We have measured step lengths parallel and perpendicular to the piezo axis as a function of the pulse duration and magnitude (see Fig. 2). Here we have used single, digitally generated, cycloids applied repeatedly (10–100 times) and we have measured the average step size that the tip apex has taken (using an optical microscope). From Fig. 2 one can see that steps ranging from about 0.5 to

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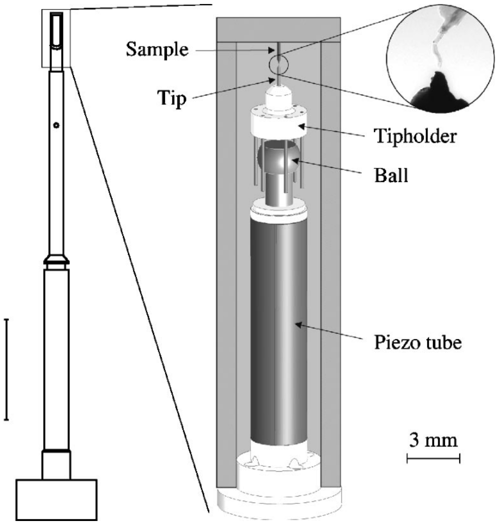

FIG. 1. Schematic illustration of the side-entry holder and its STM head with a three-dimensional coarse motion mechanism. The inset shows a TEM image of a carbon nanotube (about 20 nm in diameter) which has been selectively approached, *in situ*, with a gold tip.

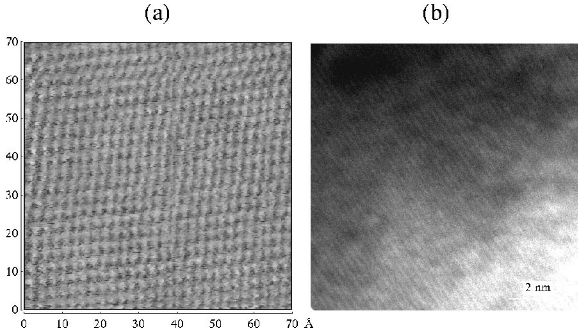

FIG. 3. (a) STM image of HOPG, taken inside the TEM using constant height mode (sample bias$=-20$ mV) and (b) high magnification TEM image of a mechanically cut gold tip (2.3 Å between adjacent lattice fringes).

30 μm can easily be achieved perpendicular to the piezo axis, while the steps along the axis are substantially shorter, 0.05–1.5 μm. This is partly due to the fact that the piezo moves much less in the direction along the axis (± 1.2 μm) than perpendicular to the axis (± 14 μm). It is also very different motion perpendicular to the axis, since the tip holder rotates around the sapphire ball and there is a lever effect that magnifies motion of the tip. Thus the step lengths in this direction will also depend on the length of the tip and the position of the tip holder relative to the sapphire ball. The strength of the springs will also affect the step lengths, both in the direction parallel and perpendicular to the piezo axis. In the limit of very weak springs the influence of gravity would make the tip point downward as one tries to engage inertial sliding. The influence of gravity is negligible in the stiff limit. In the present work we have used quite stiff springs and we have measured a static friction force of around 70 mN along the piezo axis (note that this depends on the position of the tip holder relative to the sapphire ball). Since the tip holder, including the tip, only weighs approximately 0.12 g, the influence of gravity is minimized and an acceleration of above 600 m/s^2 has to be reached in order for the tip holder to overcome static friction (for the direction along the piezo tube). Such high accelerations require fast electronics and high mechanical resonance frequency in order for the end of the piezo to actually follow these rapid movements.

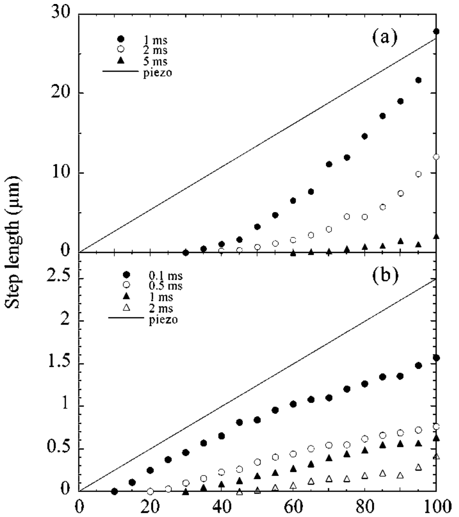

FIG. 2. Measured step sizes as a function of the amplitude (100%=140 V) of the voltage pulse for different pulse durations (i.e., the base width of the cycloid) in the direction (a) perpendicular to the piezo axis and (b) along the piezo axis. The solid line shows the distance traveled by the tip due to piezo deflection, provided that it can follow the rapid voltage pulse applied.

The material and surface finish of the ball are important for the performance of the inertial sliding mechanism. We have chosen sapphire because it is hard and it can also be manufactured with high accuracy and a good surface finish. Sapphire is commonly used for inertial sliding mechanisms and gives good sliding motion against metals, in this case springs that are made of Cu/Sn (6%). The drawback is that the sapphire is not electrically conducting and we need an extra wire for electrical connection of the tip. This was made using a thin Cu wire (50 μm in diameter) protected with varnish. Extra care had to be taken while positioning the wire in order not to exert any additional force on the tip holder and thus interfere with the inertial sliding motion. The inertial sliding mechanism was also tested in vacuum and we saw no substantial difference from the values obtained in air. The smallest, reliable and reproducible, step values are approximately 5% of the piezo range (for both directions) and this is more than accurate enough to work as a coarse approach mechanism for a STM.

The performance of the TEM and STM modes were tested in a Philips CM200 super twin FEG using electronics and software from Nanofactory Instruments AB (Ref. 16) to control the piezo movement and sliding mechanism. Figure 3(a) shows a typical constant-height STM image of highly oriented pyrolitic graphite (HOPG), while Fig. 3(b) shows a high magnification TEM image of a gold tip. Resolution on the atomic scale is achieved in both imaging modes, illustrating that the influence of mechanical vibrations and other sources of noise are very low. We believe that increasing the mechanical resonance frequency of the construction could further reduce these noise levels. From Fig. 2 it is clear that one could use an even shorter or stiffer piezo, since coarse motion works for amplitudes well below the maximum amplitudes used here. Alternatively, one could also reduce the size of the tip holder in order to reduce its mass. These changes would all increase the resonance frequency and reduce the noise levels even further.

In summary, we have shown that it is possible to fit a STM, with a three-dimensional coarse approach mechanism inside a regular TEM holder. Our compact design enables atomic scale resolution in both TEM and STM imaging modes. The three-dimensional coarse mechanism adds a new dimension to experiments that can be performed inside the TEM. Our instrument can be considered more as having a small electrically conducting probe inside the TEM, rather than only performing regular STM experiments inside the TEM. Experiments such as probing electrical conductance at different sample positions can thus readily be performed, without the need for extra sample preparation, in order to align sample and tip features.[17]

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