A new high-resolution two-dimensional micropositioning device for scanning probe microscopy applications

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We report on the development of a new two-dimensional micropositioning device, or walker, which is capable of moving across very large distances (in principle unlimited) and with a very small step size (as small as 100 Å/step) in both directions. Based on a unique tracking design, the motion is extremely orthogonal with very little crosstalk between the two directions. Additionally, there is no detectable backlash in either direction. The walker performance has been extensively tested by using a position-sensitive proximitor probe. Tests have been done between 77 and 300 K. However, we project that the walker will be able to operate at temperatures as low as 4 K. This walker system has shown extremely reliable performance in a UHV environment for use with scanning tunneling microscopy and has been especially useful for cross-sectional scanning tunneling microscopy and spectroscopy studies of semiconductor hetero- and homostructures. We show one example of results on the (AlGa)As/GaAs heterostructure system.

I. INTRODUCTION

Since the invention of scanning tunneling microscopy in 1981 by Binnig and Rohrer,[1] various kinds of systems have been developed for bringing a sample to within a very small distance from a tip (usually less than 1 μm). Among these are the inchworm, the stepping motor, the louse system, and various other mechanical screws. Additionally, a number of other translation devices based upon the principle of the piezoelectric response have been invented. Early versions utilized a periodic clamping and unclamping of several feet and the expansion and contraction of the piezo element in between and were referred to as "quasistatic devices."[2] Later, more dynamic designs began using the piezo element to provide a periodic acceleration of a supporting base or the translation stage itself. These operated on the principle of stick-slip motion such as that used by Lyding *et al.*[3] The walker system we have developed is of the latter type but is unique in that it provides orthogonal, independent motion with negligible backlash or crosstalk. Additionally, it exhibits other highly desirable properties such as the ability to climb steep slopes.

II. DESIGN PRINCIPLES

There are several important design considerations which must be discussed in order to understand how this walker achieves such high performance. First is the use of a tracking design which provides for the extreme orthogonality and self-alignment of the motion. Next, we use a piezoelectric "piston" to apply impulse forces on the walker in such a way that any backlash or glitches are essentially nonexistent. Finally, a magnetic clamping device allows the walkers to move reliably even at large angles of inclination.

Some dynamic piezoelectric translators utilize the piezoelectric action to shake a base or support upon which sits the translation stage. In most cases, this results in coupling between x and y directions and undesired rotation of the walker. In our design, this is eliminated by the use of two sets of tracks which are orthogonal to each other. The principle is much the same as that used in common micrometer-driven translation stages. As illustrated in Fig. 1, the walker system consists of three stacked layers. The x-direction walker (stage 1) is made of a 1×1 in. square piece of rigid material (typically stainless steel or macor) having a thickness of about 0.16 in. (which has two sapphire rods attached to the bottom). This walker slides in a track consisting of one v-groove and one rectangular-shaped groove on a base of the same dimensions as the walker, similar to the design of Niedermann *et al.*[4] The z-direction walker (stage 2), having dimensions similar to stage 1, rides on top of stage 1, sliding in a similar pair of grooves. In the case where stainless steel is used, the mass of each stage is about 25 g, including the counterweight and sapphire rods. However, it is important to realize that stage 2 usually carries a sample holder of roughly 5–10 g and that stage 1 is carrying the weight of stage 2 and the sample holder.

While the rectangular-shaped groove provides a smooth supporting surface, the v-shaped groove constrains the motion to one direction. The walker therefore is self-aligning. While this self-aligning feature can be achieved with the use of just three ruby or sapphire balls, the frictional force between the balls and the surface will vary according to the uniformity of the track, and local track imperfections can have serious detrimental effects on the motion. With the sapphire rod design, on the other hand, the effective frictional force is the average force over the length of the sapphire rod in the v-groove. This results in a very uniform frictional force where the influence of local track imperfections is greatly reduced. Finally, the self-alignment along the track together with the uniform frictional force makes this walker design free of crosstalk due to motion in the orthogonal direction.

Shear piezoelectric materials have been used in walker designs, but they typically cause backlash motion due to the fact that the sample is riding on top of the active piezo element. In our design, the motion is achieved by using a piezoelectric tube (piston) with a small counterweight attached to the end (see Fig. 1). The piezo tubes used are typically 0.5

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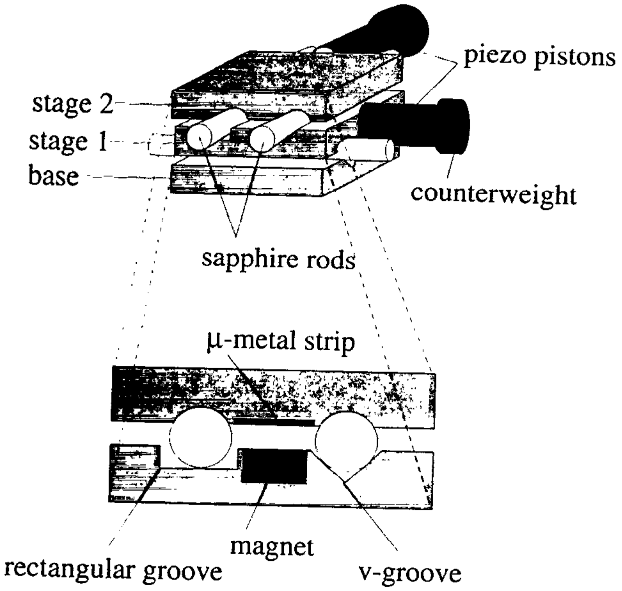

FIG. 1. Illustration of our walker design. The top stage (z direction) rides in tracks on the middle stage (x direction) which in turn rides in tracks on the bottom plate. The v- and rectangular-shaped grooves provide for the uniformity of the motion.

in. in length by 0.25 in. in outer diameter with a 0.020 in. wall thickness. We have used PZT-4, PZT-5A, and PZT-5H; they all work fine. PZT-4 and 5A each have substantially higher Curie temperatures than 5H and so may be more resistant to depoling during bakeouts. On the other hand, PZT-5H has a much larger response at room temperature than either 4 or 5A. The mass of the counterweight is 1.5–2.0 g. Impulse forces are obtained by applying a voltage waveform to the piezo tube. Since each impulse force acts like a single "kick" to the walker, the resulting walker motion is free of backlash.

The speed of the walker can be characterized by two parameters: the single step size and the driving frequency. The single-step size can be easily controlled to any value between 100 and 1000 Å by tuning the driving voltage amplitude. The typical driving frequency is between 1 and 4 kHz. The speed is the product of the single step size and the driving frequency.

The specific waveform we apply to the piezo tube is also very important. The simplest waveform which has been used is the sawtooth. However, as explained by Renner *et al.*,[5] this waveform has the disadvantage of having a reverse acceleration during each cycle which can cause backlash. The more ideal waveform to use in this situation is the cycloid since it has only one strong acceleration peak per cycle.[5] The typical peak voltage we use is around 300 V although the threshold for motion may occur as low as 80–100 V. In some cases, we may apply up to 600 V, depending on the specific walker being used. The combination of cycloid waveform and piezo piston results in reliable motion which is free of backlash. The impulse force occurs during the portion of the waveform where the acceleration exceeds a certain critical value, namely near the region of the cusp. This critical value depends on the mass of the walker but more importantly upon

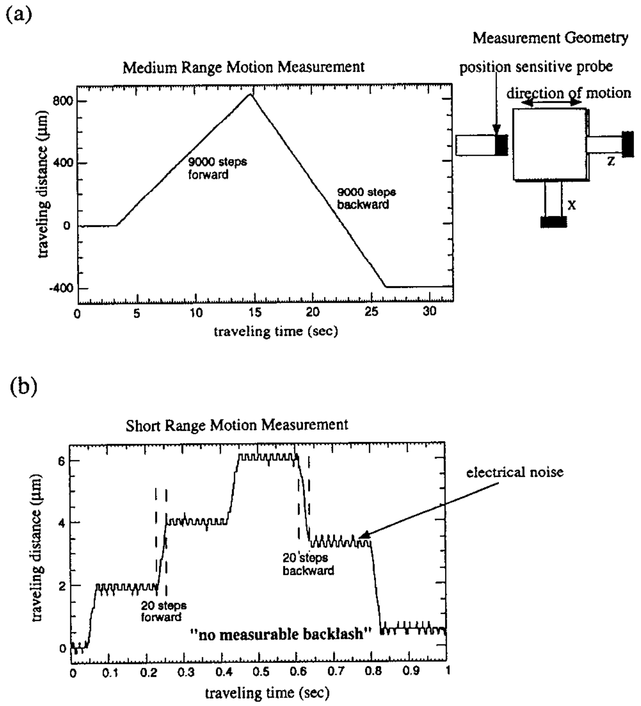

FIG. 2. (a) Medium-range motion measured with a proximitor probe. The walking speed is extremely uniform during 9000 steps in both forward and backward directions. (b) Short-range motion measurement. No observable backlash can be seen at the beginning or at the end of each set of 20 steps. The small oscillations are electrical noise in the measurement circuit, indicating the resolution limit of the proximitor probe.

the frictional force between the sapphire rods and the track. The uniformity of the motion is therefore dependent upon a uniform coefficient of friction (provided by the sapphire rod/v-groove averaging effect) and upon a uniform normal force.

For this reason, a magnetic force mechanism has been built into the system to provide such a uniform normal force between the sled and track even at angles of inclination away from the horizontal. This is accomplished by a small magnet inserted into the center of stage 1 and a thin strip of μ-metal placed between the tracks of the base plate and between the sapphire rods of stage 2. The μ-metal strips serve two functions. First, they are attractive surfaces for the magnet, thus providing the constant normal forces. Second, they shield the magnetic field by terminating it on those surfaces. Furthermore, we have found that such a magnetic force mechanism is superior to a spring clamping mechanism since it will not have any unwanted lateral force components which can cause jerkiness in the motion, especially during direction reversals.

III. PERFORMANCE RESULTS

All of the calibration measurements were carried out at room temperature using a proximitor device. However, the device has been tested in a low temperature UHV environment where we obtained atomic resolution images of GaAs.[6] Figure 2(a) shows a plot of the walker motion for 9000 steps in both the forward and backward directions as a function of time. Also shown is the measurement geometry. As can be seen, the motion is very uniform over a long range but shows some asymmetry in walking speed. This asymmetry may be

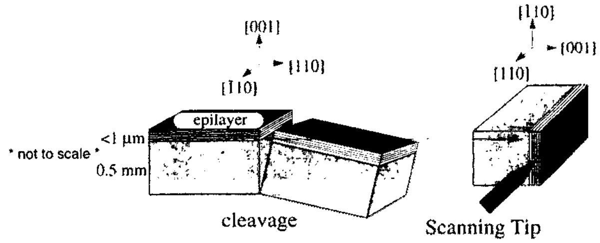

FIG. 3. Cleaving a semiconductor sample in UHV. A fresh (110) surface is exposed upon cleaving, revealing the heterojunctions within the epilayer in cross section.

attributed to the asymmetry of the piezo tube polarization. The result is slightly faster walking in the backward direction than in the forward.

The absence of backlash is displayed in Fig. 2(b) which shows the walker motion for a short number of steps (20) in both forward and backward directions. As claimed, there are no noticeable backlash glitches even upon switching directions from forward to backward. It is important to point out that the small oscillations seen in the figure correspond to electrical noise which limits our measurement resolution. This feature of no observable backlash is important for scanning tunneling microscopy (STM) in situations where the tip is very close to the sample, especially in applications such as will be described in Sec. IV.

As mentioned before, we have found that the magnetic force mechanism is a dramatic improvement over previous spring-loaded force designs. However, as the walker moves away from center, the position of the magnet moves toward the edge of the μ-metal strip. Because the μ-metal terminates the magnetic field, the magnetic force in that region is not perfectly normal to the surface. As a consequence, we observe the walking speed to decrease slightly because of this small lateral force. However, this is not a limitation since the effect can easily be eliminated by simply increasing the length of the μ-metal strip. With a reasonably strong magnet, our walker was able to climb a slope as great as 30° to the horizontal. Of course, this is not necessarily any kind of limiting value. By comparison, a walker without any force mechanism would cease to move at around 7° because of the $\sin\theta$ dependence of the tangential gravitational force.

IV. APPLICATION TO STM

One of the motivations behind the development of this high-precision walker system was its application to the study of semiconductor heterostructures. To understand why this is important for such investigations, one must consider the technical difficulty involved in locating the junctions. A typical sample consists of a substrate which is approximately 0.5 mm in thickness and an epilayer containing the heterostructures which is approximately 1 μm or less in thickness. Since we are interested in investigating the structural and electronic properties across the junctions, it is necessary to study the cross-sectional surface which must first be prepared by cleaving the sample. This is done by pushing the sample along the $[00\bar{1}]$ direction as shown in Fig. 3.

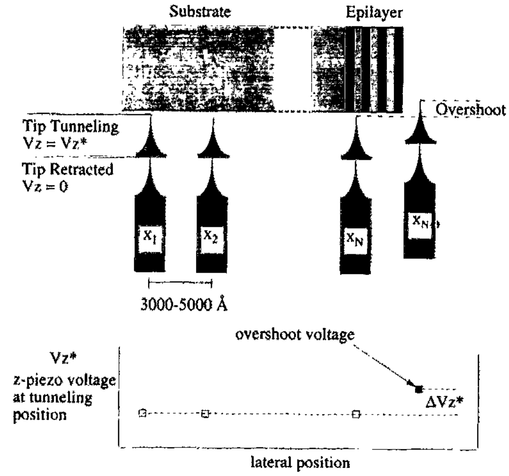

FIG. 4. Schematic diagram showing how the tip is positioned within the region of the epilayer. A reference z-piezo voltage Vz^* is established by repeatedly moving the tip into the tunneling regime, retracting the tip, and moving the sample sideways. The overshoot is indicated by a sudden increase in Vz over the reference Vz^* whereupon the tip is retracted and the sample is moved back into the epilayer region.

To study the heterostructures with STM, it is necessary to position the tip of the STM within the epilayer region. Herein lies the difficulty. Since typical optical microscopes used with UHV STMs have working distances of about 15–20 cm, it will be very difficult to position the tip within the epilayer region since it is so thin. To overcome this difficulty, one approach has been to use a UHV scanning electron microscope (SEM) to aid in locating the junctions. This has proven to be successful but quite expensive.[7]

To solve this difficulty, we employ an epilayer-locating technique which is based upon the properties of a reliable and predictable two-dimensional translation system such as our walker. This by no means implies that we are the only group which has succeeded in using an edge-finding technique such as this. Others have used similar but not identical algorithms.[8–10] Illustrated pictorially in Fig. 4 is the method which we use to locate the epilayer region. In short, the sample is stepped laterally until the z-piezo voltage exceeds the previous voltage at which tunneling occurred, indicating the edge of the sample. Stepping back places the tip within the epilayer. Included in the figure is the basic algorithm for this approach. Such an approach makes locating the epilayer region extremely easy.

The success of this method depends primarily upon two things. First, the sample must be extremely flat all the way up to the edge. Variations in the topographic height must not exceed about 100 Å. This requirement is satisfied with a suitably step-free cleave. The second requirement is a two-dimensional sample mover which is free of backlash and crosstalk. Without this, it will be very difficult to avoid crashing the tip.

Figure 5 shows an example of a UHV STM atomic resolution image of (AlGa)As/GaAs heterojunctions. A discussion of this data will be described in a forthcoming publication.[11] In addition, many other cross-sectional STM results have been obtained to date using a walker similar to

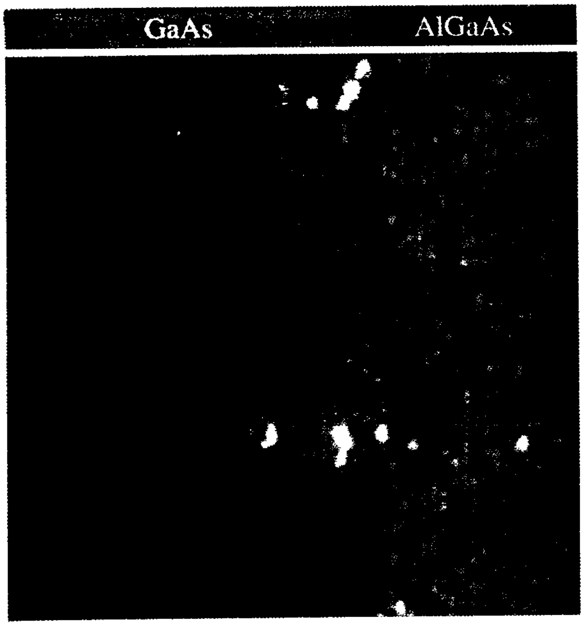

FIG. 5. UHV STM atomic resolution image of (AlGa)As/GaAs heterojunction region. Our walker design enables the successful location of the epilayer region at the edge of a cross-sectional surface.

the one described here.[12–16] These results clearly establish the suitability of our walker design for use in cross-sectional STM.

V. DISCUSSION

A high-performance, two-dimensional walker system has been described which possesses several unique features. First, the traveling range is in principle unlimited while the minimum step size can be as small as 100 Å. Second, the two directions are orthogonal to each other and do not exhibit backlash in either direction nor crosstalk between directions. Third, a magnetic clamping mechanism has been employed which allows the walker to move up steep inclines. Fourth, the walker system is completely UHV compatible, can operate at low temperatures, and has been successfully incorporated into an STM. Finally, we should point out that the operational parameters quoted previously are nominal values which are applicable only for the walker described here. Since the threshold voltage is really dependent on the frictional force along the direction of the track, which in turn depends on the normal force between the walker and the track as well as the roughness of the track, optimal operating parameters need to be determined for each walker system on a case-by-case basis.

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