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All low voltage lateral junction scanning tunneling microscope with very high precision and stability

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We describe the first lateral junction and fully low voltage scanning tunneling microscope, featuring very high precision, stability, compactness, and image quality (highly oriented pyrolytic graphite atomic resolution images). In its core, the tip and sample each sit on one of two parallel-mounted piezoelectric tube scanners so that the tip-sample gap is regulated along the scanners' pairing direction. The scanner's large lateral deflection provides a large gap regulation range even under low voltages, allowing exclusively using only low voltage (less than ± 15 V) operational amplifiers to precisely implement the coarse (inertial slider) and fine approach, feedback control, and hence the entire electronics. Because the scanners are identical and adjacent, thermal drifts are minimal.
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I. INTRODUCTION

The scanning tunneling microscope (STM) has grown into a crucial tool in surface science and engineering since its invention.[1] Homemade and commercial STMs have become numerous now,[2–5] but most, if not all, of them incorporate high voltage (>20 V) devices such as operational amplifiers (op amps) and transistors in their coarse approach, fine approach and feedback control circuits.[2] Reasons are several: (1) the coarse approach (via piezoelectric motor, for instance) typically relies on high voltage to produce enough step length so as to overcome friction and backlash; (2) after the coarse approach is done, the fine approach that follows has to use high voltage to push the tip and sample close enough to generate tunneling current, owing to the large tip-sample gap left over by the high voltage coarse approach; (3) in cases where the sample surface corrugation is considerable, a large tip-sample regulation range is necessary for the tip to follow the surface topography, which also calls for high voltage.

Obviously, the drawbacks of employing high voltages in a STM are rather severe, including high drift, offsets, noise, cost, and low speeds associated with the high voltage devices used, which inevitably downgrade the performance and precision of the STM significantly. In this paper, we, for the first time, report a lateral junction STM in which all voltages are less than ± 15 V. As expected, this totally home-brewed STM demonstrates very high levels of precision, stability, and image quality. The core is the low voltage low-drift implementation of a large step-length inertial slider and a large regulation-range junction structure without sacrificing the scan range dramatically.

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II. STM UNIT

In the core (Fig. 1), two identical piezoelectric tube scanners (PT130.24 from Physik Instrumente with length $L=30$ mm, inner diameter $D=9$ mm, and wall thickness $d=0.5$ mm) are glued (H74F epoxy of Epoxy Technology) on a base side by side 1 mm apart [Fig. 1(b)]. The tip and sample sit on the scanners with the tip-sample gap being regulated along the scanners' pairing direction (Z direction in Fig. 1). One scanner (called gap regulation tube or GRT) is used as the inertial slider actuator and tip-sample gap regulator, while the other (called surface scan tube or SST) is for the sample imaging scan. The base is a circular sapphire block ($\phi 32\times 4$ mm^2 thick). The titanium rail piece [Fig. 1(a)] supports and guides the free lying inertial slider ($\phi 7 \times 8$ mm^2 long) which is made of tungsten for higher inertia. The rail piece is glued on the GRT with silver paint. The slider also serves as the sample stage, to which the sample is attached vertically with silver paint. A sapphire ring spacer is glued (H74F epoxy) for insulation between the rail piece and the GRT as well as between the tip holder and the SST as shown in Fig. 1(b). The tip holder is a tiny titanium piece with a 0.5 mm horizontal hole in which the tip can be inserted and secured by a set screw.

This unique junction orientation, flipped 90° from the conventional axial direction of the scanner, has twofold importance: (1) making the tip-sample gap insensitive to the thermal drifts of the GRT and SST and only slightly sensitive to the thermal expansion of the base due to the small separation of the GRT and SST on the base (this sensitivity can nevertheless be reduced by choosing a low thermal expansion material for the base); (2) making the tip-sample gap be regulated by the lateral (not axial) motion of the GRT, leading to a large gap regulation range even with low lateral deflection voltages. This is because the axial and lateral displacements are roughly given by $\Delta L=d_{31}LV/d$ and

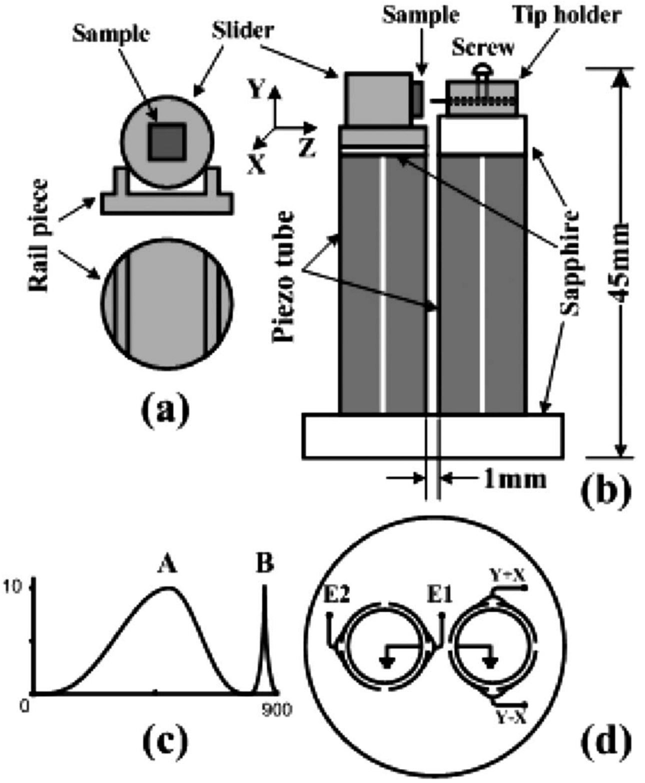

FIG. 1. A schematic of the STM unit with the definitions of X, Y, and Z directions; (a) structure of the inertial slider; (b) a side view of the STM unit; (c) driving signal; (d) electrode connections.

$\Delta X = 0.9 \Delta L \times L/D$, respectively,[6] with the axial being smaller than the lateral by a factor of L/D (≈ 3 in our case), implying the replaceability of high voltages with the lower ones. Here L is the length of the tube scanner, D is the inner diameter, d is the wall thickness, d_{31} is the strain coefficient, and V is the operating voltage.

The scanner core, excluding the base is only 21 mm wide and 45 mm tall. The base needs to be only slightly wider than 21 mm. We employed a larger base for easy testing and wiring. This design is very compact and solid, making it resistant to vibrations and well suited to various extreme conditions (UHV, ultralow temperature, ultrahigh magnetic field, etc.)

The electrodes of the GRT and SST were connected according to Fig. 1(d). The inner electrode of each tube was grounded and the four quarter-cylindrical outer electrodes of each tube were connected to form two semicylindrical electrodes. A differential signal on the semicylindrical electrodes E1 and E2 of the GRT bends it toward or away from the SST, regulating the tip-sample gap in the Z direction, while the two semicylindrical electrodes $Y-X$ and $Y+X$ of the SST perform a two-dimensional scan relative to the GRT (i.e., the sample) in the X-Y plane (see Fig. 1). In this electrode connection scheme, the displacements of the GRT and SST are along the diagonal directions of the squares formed by the quadruplet electrodes, hence increasing the gap regulation range of the GRT and the scan range of the SST by a factor of $\sqrt{2}$ compared to the case of ungrouped electrodes.

This connection scheme gave a final lateral deflection rate of 0.1 μm/V for each piezotube, much larger than the

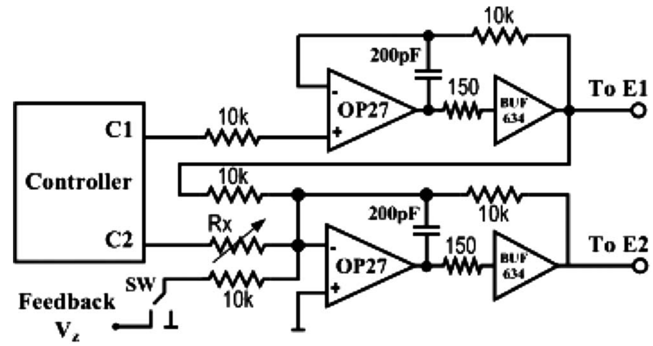

FIG. 2. A schematic of the inertial slider control circuit.

axial 0.04 μm/V. This means a 3 μm range for X and Z can be achieved with ± 15 V low driving voltages (the power supply voltages for standard low voltage op amps). The downside of this design is that the Y scan range is low since it comes from the axial motion of the scanner. The Y range can nevertheless be doubled if the opposite axial motions of the SST and GRT are exploited for the Y scan, giving rise to a Y range of 1.2 μm with ± 15 V. It should also be noticed that the lateral resonant frequency $f_{0,L}$ of a piezoelectric tube scanner is typically lower than its axial counterpart $f_{0,A}$ by a factor of 4 to 5,[7] making it difficult to build a fast lateral junction STM. However, $f_{0,L}$ is in general higher than 1 kHz (Ref. 7) and a normal speed lateral junction STM is thus feasible.

The signal waveform driving the inertial slider is presented in Fig. 1(c); it is a modification of Ref. 8. It consists of a wide hill followed by a needlelike pulse. The wide hill represents a slow approach and withdraws to predetermine whether a tip-to-sample crash will happen in the next move. Our inertial slider walked stably even with a driving voltage as low as 4 V. Thus, the coarse approach could be done solely with low voltage circuits. Because no high voltage was used in the coarse approach, the fine approach that followed to get controlled tunneling current did not require high voltage either.

III. CIRCUIT DESIGN

To drive the inertial slider (capacitive load) without deforming the driving signal, we apply BUF634 (250 mA high speed buffer from Texas Instruments) to boost the OP27 (Analog devices) output current, resulting in a composite buffer[9] (see Fig. 2). The driving signal [see Fig. 1(c)] is generated at port C1 of the controller (PXI-8106RT, National Instruments) and sent to a composite buffer which drives the GRT's E1 electrode [Fig. 1(d)], forming one half of a push-pull signal. The E1 electrode signal is also inverted and applied to the E2 electrode, completing the other half of the push-pull signal on the GRT. The complete coarse approach procedure is a repetition of slow approach and withdraw for tunneling current checking [part A of Fig. 1(c)] followed by rapid inertial stepping [part B of Fig. 1(c)].

The coarse approach stops when the tunneling current is sensed. The voltage C2 from the controller is reduced and added to the GRT electrode E1 to fine approach and hold the tip and sample in a controlled manner with a preset tunneling

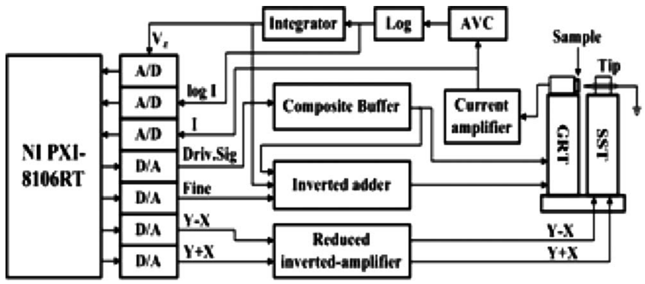

FIG. 3. Block diagram of the feedback control. AVC: absolute value circuit, Log: log amplifier, Driv.Sig: driving signal, V_z: feedback voltage, I: tunneling current.

current flowing in between. We then start constant height imaging as follows: the feedback control is disconnected (Fig. 2); the scan voltages generated by the controller are reduced by an inverting amplifier (OP27, not shown) and then applied to the SST electrodes $Y-X$, $Y+X$, respectively; finally, the scan voltages and the tunneling current data are processed in ORIGIN PRO 7.5 to form images.

To work in constant current mode, the fine approach voltage C2 is set to a fixed value (normally zero). The feedback control system (see Fig. 3) consists of a homemade transimpedance current amplifier, an absolute value circuit (AD630 of Analog Devices), a logarithmic amplifier (LOG102 from Texas Instruments), and an integrator (LTC1150 by Linear Technology). The feedback control voltage V_Z obtained from the tunneling current is added (via switch SW in Fig. 2) to the GRT electrode E2, which regulates the tip-sample gap in order to maintain a constant tunneling current. We wrote all the controlling software ourselves in LABVIEW 8.20 with the real-time module installed in the PXI-8106RT (National Instruments).

In case the sample surface is rough, a larger tip-sample regulation range is required in order to track the surface topography. Still, no high voltage is needed since low voltages are sufficient in accomplishing a large GRT lateral deflection, giving a big tip-sample regulation range. All in all, we have exclusively used only low voltage high precision op amps and devices including the PXI-8106RT to build the whole STM electronics with low noise, low drift, and high reliability.

IV. TEST AND OPERATION

The STM was tested by imaging highly oriented pyrolytic graphite (HOPG) (GYBS/1.7, type ZYB from NT-MDT). The coarse approach stepping speed of the slider was set to 0.1 mm/min. Figure 4 displays the constant height raw-data image of the HOPG taken in air at room temperature under a bias voltage of 100 mV (sample positive). The scan rate was 8.3 lines/s. A cut, 0.15 mm thick Pt90/Ir10 tip (from Goodfellow) was used. The STM was put in a home-built sound-isolated box on a vibration damped table. The hexagonal lattice of the HOPG is shown in Fig. 4 with clarity

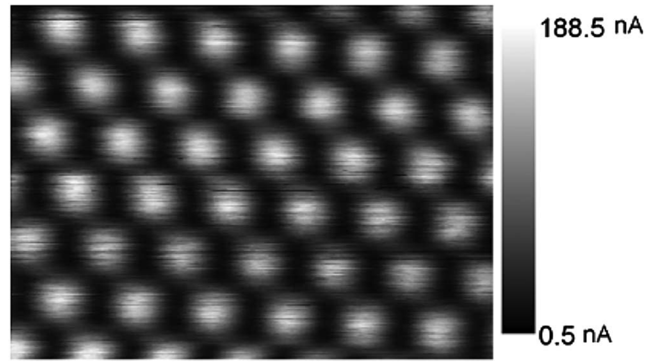

FIG. 4. 1.57×1.14 nm^2 raw-data image of HOPG taken in air, constant height mode, 100 mV bias (sample positive).

comparable to an extremely high quality image obtained using a tungsten tip in UHV and low temperature.[10,11]

V. CONCLUSION

We have developed a compact, low-drift STM using only low voltage (less than ±15 V) devices without downgrading the scan size and tip-sample regulation range. The heart is a lateral regulated junction structure which implements coarse approach, fine approach, and feedback control under low voltages. The electronic noise, precision, offset, speed, temperature drift, etc., are all greatly improved due to the low voltage devices exploited. Mechanical thermal drifts are minimized as well since the lateral tip-sample gap is not impacted by the vertical tube scanners' drifts.

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