Scanning Tunneling Microscope Control: A Self-Tuning PI Controller Based on Online Local Barrier Height Estimation

Farid Tajaddodianfar, S. O. Reza Moheimani, Fellow, IEEE, and John N. Randall, Fellow, IEEE,

Abstract—We identify the dynamics of a scanning tunneling microscope (STM) in closed loop and show that the plant dc gain is proportional to the square root of local barrier height (LBH), a quantum mechanical property of the sample and/or tip that affects the tunneling current. We demonstrate that during a scan, the LBH may undergo significant variations and this can adversely affect the closed-loop stability if the controller parameters remain fixed. Feedback instabilities increase the risk of tip-sample crash in STMs. In order to improve the closed-loop performance, we estimate the LBH, on the fly, and use that to adaptively tune the proportional-integral (PI) controller parameters. Experimental results obtained with the self-tuning PI controller confirm the improved STM performance compared to the conventional fixed-gain PI controller. Additional experiments confirm effectiveness of the proposed method in extending the tip lifetime by lowering the chance of a tip/sample crash.

Index Terms—Lyapunov filter, local barrier height (LBH), parameter estimation, proportional-integral (PI) controller, scanning tunneling microscope (STM), self-tuning, work function.

I. INTRODUCTION

In scanning probe microscopy, an extremely sharp probing tip is moved over a sample to collect surface topography information taking advantage of a physical phenomenon that takes place between the tip and sample. In scanning tunneling microscope (STM), this phenomenon is the tunneling current, a quantum mechanical effect that refers to the electrical current established due to the tunneling of electrons through the space between a conducting tip and surface when their relative distance is below a nanometer and a bias dc voltage is established between them. This current is modeled as an exponential function of the tip-sample distance. While scanning, atomic-scale surface features cause a change in the tunneling current.

A control system measures this current and adjusts the vertical tip position to compensate for the current variations and keep the current constant. Thus, the controller command maps a topography of the surface. Fig. 1 displays a schematic of the STM operation in the constant current mode.

Over the past three decades, the STM has found a myriad of applications in numerous fields leading to ground-breaking observations (see [1]–[4]). The early works on STM concentrated on imaging. However, soon it was realized that the STM tip could be used as an effective tool for patterning the surface with a resolution down to a single atom through lithography [5]. Atomic-scale lithography continues to be an active research topic in nanotechnology [6]–[9].

Poor performance of the STM control system results in tip-sample crash, a prevalent failure in STMs. Few attempts have been made to improve the STM control system. Oliva et al. [10] analyzed the STM control system to obtain optimal imaging conditions [11] and determine optimal feedback parameters [12]. Ahmad et al. [13], [14] discussed the design of a robust controller for STM. Bonnail et al. [15] modeled the STM control system and proposed a sliding mode scheme for switching between positive and negative feedback control in order to improve the stability.
Blanvillain et al. [16] used the tunneling junction to build a sub-nanometer-resolution position sensor which takes advantage of a control system similar to that of the STM. Recently, we showed that the stability of the STM control system is affected by variations in the local barrier height (LBH), a quantum mechanical property of the tip and sample [17]–[20]. The LBH variation has long been known to the STM researchers [21]–[26]. However, to the authors’ best knowledge, its adverse effects on the robustness of the STM control system have never been reported.

In this paper, we present further analysis and experiments to support the observation that LBH variations lead to changes in the feedback control loop gain, with adverse effects on the STM closed-loop stability. We use the joint input-output approach [27] to determine frequency response of the closed-loop system. We demonstrate that LBH variations affect the dc gain of the identified open-loop transfer function (TF). Furthermore, we investigate stability of the STM closed-loop system under proportional-integral (PI) control and show that LBH variations may lead to instabilities if PI gains are fixed. Based on this analysis, we propose a self-tuning PI controller that continuously adjusts PI gains according to the LBH measurements in order to prevent instability. We present experimental results showing that the LBH is a varying parameter that depends on both tip and sample properties. Moreover, we present experimental results confirming the enhanced stability and extended tip lifetime under the proposed control method.

In the remainder of this paper, we briefly discuss the theory of tunneling current and present the control system architecture in Section II. Then in Section III, we discuss a method for closed-loop system identification. In Section IV, we discuss online estimation of the LBH and describe the self-tuning PI controller. Section V continues with experimental results. Final conclusions and remarks are given in Section VI.

II. CONTROL SYSTEM STRUCTURE OF STM

In this section, we briefly describe the custom-designed STM that was used in our experiments. We also briefly discuss the tunneling current physics and the control system architecture of the existing STM.

A. Experimental Setup

The STM control system runs on a 20-bit digital signal processor operating at 50-kHz sampling frequency. This system is used for all data acquisition and control purposes and is commercially known as ZyVector. A Femto DLPCA-200 transimpedance preamplifier is used to detect the tunneling current. For frequency-domain measurements, we used an ONOSOKKI CF-9400 FFT analyzer. In addition, some of the time-domain measurements were collected by a dSpace Microlab Box. Further details of the experimental setup are described in [17].

B. Tunneling Current and the LBH

Quantum mechanical calculations suggest that the electrical current which tunnels through the vacuum between an STM tip and sample is proportional to the applied bias voltage and is an exponential function of the tip-sample separation [22], [28]. A simplified model is [24]

$$i = \sigma V_b e^{-1.025 \sqrt{\delta}}$$

(1)

where \(V_b\) is the bias voltage, \(\sigma\) is a parameter depending on the material and geometry of the tip and sample, and \(\delta\) (in \( Å\)) is the energy barrier thickness which is approximately equal to the geometrical tip-sample separation [24]. \(\phi\) (in eV) is called “work function” or “Barrier height” which by definition is the minimum energy required to remove an electron from a solid. In quantum mechanics, energy of electron in vacuum is higher than its energy in solid and this difference, i.e., the work function, acts as a barrier preventing electrons from leaving the solid [22], [29]. A preamplifier of gain \(R\) is used to convert the sub-nanopere range tunneling current \(i\) in (1) to a measurable voltage, the natural logarithm of which is then taken to linearize the model. This gives

$$\ln(Ri) = \ln(R\sigma V_b) - 1.025 \sqrt{\delta}$$

(2)

which indicates that for constant \(\sigma\) and \(V_b\) the logarithm of tunneling current is proportional to the tip-sample separation, assuming that \(\phi\) is constant. This linear relationship between \(\ln i\) and \(\delta\) is crucial to the operation of STM which ultimately maps a surface topography correlated with \(\delta\) by keeping the current constant using a linear feedback.

In addition, (2) suggests that, for constant \(\sigma\) and \(V_b\), the logarithmic derivative of current with respect to the tip-sample separation provides a measure of the barrier height [21], [24], [30]

$$\phi = 0.952 \left(\frac{d}{d\delta} \ln Ri\right)^2.$$  

(3)

It is well understood that the barrier height depends on the physical properties of the tip apex as well as those of the sample surface atoms into which the current tunnels [24]. Thus, the barrier height is a local effect and is subject to change. Based on this understanding, parameter \(\phi\) can be used to produce another image. This is referred to as the LBH image, and provides additional information about the physical and chemical surface characteristics [22], [23], [31], [32].

Experimental investigations have shown that, for the range of tip-sample separation \(\delta\) over which the STM usually operates, \(\phi\) is nearly independent of \(\delta\) [21], [23], [24]. This assures that the linearization provided by (2) remains effective for normal operating conditions in STM.

C. Closed-Loop Structure

The effective instantaneous tip-sample gap, \(\delta\), can be described as

$$\delta = d_{hm} - d_0 - h - d_{qf}$$

(4)

where \(d_{hm}\) represents the tip-sample separation when the tip is at its home position, \(d_0\) stands for changes in the tip-sample gap due to the sample distortion or drift, \(h\) is the surface features height and represents the actual surface topography, and \(d_{qf}\) is the tip displacement due to the control command.
Fig. 2. (a) Block diagram of the STM z-axis control System. (b) Control block diagram with simplified tunneling current model. Exogenous inputs and outputs for identification purposes are shown in dashed arrows, and \( s = jω \) is used.

Assuming a model given by (1) for the tunneling current and using (2), the closed-loop control block diagram is simplified, as shown in Fig. 2(b). Thus, the square root of \( \varphi \) appears as a gain. In the rest of this paper, we use the simplified block diagram shown in Fig. 2(b) for our discussion.

### III. Stability and Performance Analysis

#### A. Closed-Loop System Identification

Fig. 2(b) depicts the experimental setup to identify the dynamics of STM closed-loop system. Frequency response functions (FRFs) were obtained for TFs from inputs \( u \) and \( r \) to outputs \( W \) and \( Y \). Measurements were repeated 50 times and averaged to reduce the effect of sensor noise, the four underlying systems are

\[
G_{r_2w}(jω) = \frac{W(jω)}{r(jω)} = \frac{z(jω)K(jω)z(jω)}{1 + K(jω)z(jω)G(jω)}
\]

(5)

\[
G_{r_3y}(jω) = \frac{Y(jω)}{r(jω)} = \frac{z(jω)K(jω)z(jω)G(jω)z(jω)}{1 + K(jω)z(jω)G(jω)}
\]

(6)

\[
G_{u_2w}(jω) = \frac{W(jω)}{u(jω)} = \frac{z(jω)z(jω)}{1 + K(jω)z(jω)G(jω)}
\]

(7)

\[
G_{u_3y}(jω) = \frac{Y(jω)}{r(jω)} = \frac{z(jω)z(jω)G(jω)z(jω)}{1 + K(jω)z(jω)G(jω)}
\]

(8)

where \( z(jω) \) describes the zero-order-hold model of the A/D and D/A blocks. To determine the open-loop model \( G(jω) \), we can divide the closed-loop FRFs at each frequency point to obtain

\[
G_1(jω) = \frac{G_{u_2w}(jω)}{G_{r_2w}(jω)} = z(jω)G(jω)
\]

(9)

\[
G_2(jω) = \frac{G_{u_3y}(jω)}{G_{r_3y}(jω)} = z(jω)G(jω).
\]

(10)

Having a fixed sampling frequency, \( z(jω) \) is known, and thus both \( G_1(jω) \) and \( G_2(jω) \) represent the same open-loop dynamics \( G(jω) \) after a further division by \( z(jω) \). We can also obtain the controller dynamics \( K(jω) \) by dividing (5) by (7) and (6) by (8). This can be used for validation purposes since the dynamics of the controller are already known. It is worth noting that: 1) to avoid the appearance of nonlinearities in \( \log(i) \); 2) to prevent tip-sample crash due to large oscillations near resonance frequencies; and 3) to maintain good signal-to-noise ratio (SNR) during the tests, the frequency range of interest is divided into several intervals over which the amplitude of the input signal is adjusted properly. For more discussion on the procedure and associated results see [20].

Once the open-loop FRF is obtained, a TF model is fit to the measured data. Fig. 3 shows an experimentally obtained FRF and the model fit to it. Only dominant resonances are considered while fitting the model which is obtained as

\[
G(s) = CG_0(s) = \frac{Ce^{-Ts}}{\prod \frac{1}{2πp_m} + 1}
\]

(11)

with \( C = 56.9 \text{ dB} \), \( T = 70 \mu s \), \( p_0 = 1.1 \text{ kHz} \), \( f_0 = 11 \text{ kHz} \), \( s = jω \), and other parameters given as Table I.

### Table I

<table>
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<td>( f_m (kHz) )</td>
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<td>9.69</td>
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<td>( \varsigma_m \times 1000 )</td>
<td>8.5</td>
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B. Model Uncertainties

Some of the parameters in (11) change each time the STM is operated. After each tip replacement and due to the mechanical displacement of the tip holder in the scanner, the resonance frequencies are expected to change. Repeating identification tests showed that uncertainty in resonance frequencies is no more than 10% of their nominal value. Moreover, after the current is established the resonance frequencies are kept fixed since there is no significant mechanical motion in the tip holder.

Comparing FRF models of $G(s)$ obtained from successive measurements, we observed that the dc gain of the open-loop model $G(s)$ represented by parameter $C$ in (11) is also subject to change. The observed range is 48–60 dB for the existing STM and a hydrogen passivated silicon wafer. Referring to the simplified block diagram shown in Fig. 2(b), we note that the dc gain of $G(s)$ is

$$C = -1.025 \sqrt{\varphi(a)_H} \gamma$$  \hspace{1cm} (12)

where $A_H$ is the dc gain of high-voltage amplifier $G_h(s)$ and is constant ($A_H = 13.5$ in our setup). Also, $\gamma$ is the dc gain of the piezo-actuator model $G_p(s)$ and depends on the piezo-actuator material and configuration. Since $\gamma$ is constant as well, we may attribute observed variations in parameter $C$ to the changes in parameter $\varphi$, i.e., the LBH. Regardless of the physical origin of LBH variations, one can find out from (12) that $\varphi$ directly affects the closed-loop gain.

C. Closed-Loop Stability and Performance

We use the open-loop TF model given by (11) along with a PI controller to analyze the closed-loop stability and performance of the existing STM. The PI controller is given by

$$K(s) = k_i \left( \frac{1}{s} + \frac{1}{\omega_c} \right)$$  \hspace{1cm} (13)

where $k_i$ and $\omega_c$ represent the integrator gain (in $s^{-1}$) and the corner frequency of the controller (in rad/s), respectively. We first define the closed-loop stability and performance criteria, as follows.

1) Stability: Consider the loop TF with a unit integrator gain

$$G_{lp}(s) = \left( \frac{1}{s} + \frac{1}{\omega_c} \right) G(s).$$  \hspace{1cm} (14)

For a given $\omega_c$, an integrator gain equal to the gain margin of the TF (14) makes the closed-loop system marginally stable. That is, we need $k_i < GM[G_{lp}(s)]$ for stability.

2) Bandwidth: The closed-loop bandwidth is typically required to be 100 times larger than that of the rastering frequency. The closed-loop imaging TF of the STM defined as

$$G_{img}(s) = \frac{C K(s)}{1 + K(s) G(s)}$$  \hspace{1cm} (15)

determines the closed-loop bandwidth.

3) Suppressed Ringing: To prevent the closed-loop system from exciting the piezo-actuator resonances, infinity norm of the imaging TF, must remain below a predefined threshold

$$\|G_{img}(s)\|_{\infty} = \max_{\omega \in \mathbb{R}} \|G_{img}(j \omega)\|.$$  \hspace{1cm} (16)

These criteria define three curves in the PI controller parameter space. Selecting a value for $\omega_c$, the critical integrator gain for marginal stability is given by (14). Repeating the procedure for various values of $\omega_c$ a curve shown by the solid line in Fig. 4(a) is obtained, to the left of which the stability criterion is satisfied. Also, selecting a desired minimum bandwidth $\omega_{BW}$ and following the same procedure using (15) leads to the dotted curve shown in Fig. 4(a) to the right of which the bandwidth criterion is satisfied. Selecting a desired maximum infinity norm and solving the nonlinear closed-loop equation for $k_i$, one obtains the dashed curve in Fig. 4(a) to the left of which criterion Section III-C3 is satisfied. Considering all three criteria, Fig. 4(a) suggests that PI gains must be selected in the colored area to ensure stability, fast and safe performance of the closed-loop system. Conventionally, half of the integrator gain that results in ringing is selected as the operating gain. This is shown by the black dashed-dotted curve in Fig. 4(a).

We have made experimental observations indicating that parameter $C$ in (11) takes different values spanning approximately 10 dB in range. Such a large variation in $C$ can easily affect stability and performance of the STM for which PI gains are already tuned. For instance, Fig. 4(b) shows stability and performance curves for the same system as shown in Fig. 4(a) but with parameter $C$ being 6 dB larger. The appropriate PI gains area significantly shrinks when the dc gain soars to $C = 59.1$ dB, and if PI gains are tuned for a system with $C = 53.1$ dB the closed-loop system could experience ringing or become unstable. This observation suggests that once the PI gains are tuned and fixed, the LBH variations may deteriorate system performance. We believe this is a key cause of tip-sample crash in STM.

IV. ONLINE LBH ESTIMATION AND PI TUNING

As shown in Fig. 2(b), we inject a dither signal with fixed frequency represented by $r(s)$ into the closed-loop system and track amplitude of the corresponding component in the
outputs $Y$ and $W$. Lock-in amplifier is most commonly used for this purpose [33]. Here, we use an alternative amplitude estimation method based on Lyapunov filters [33]–[35].

### A. LBH Estimation

The frequency $\Omega$ of the identification signal $r(j\Omega)$ should be greater than the closed-loop bandwidth so that it does not adversely affect the topography information at low frequencies. In addition, $\Omega$ should be small enough to avoid exciting resonance frequencies of the scanner. For the existing STM which requires a closed-loop bandwidth of a few hundred hertz and has its smallest resonance frequency near 8 kHz, we selected $\Omega = 4$ kHz.

For LBH estimation, we are interested only in the $\Omega$-component of $Y$ and $W$. Thus, we pass the measured signals through a bandpass filter (BPF) centered at $\Omega$ before sending them to the Lyapunov filter. The passband of this filter determines the bandwidth of the LBH estimator. We assign a fixed 3-dB passband of 300 Hz around the center frequency of 4 kHz, and keep the adaptive gain of the Lyapunov filter as the only tunable parameter.

Schematics of the LBH estimation method are shown in Fig. 5. For a given $r(j\Omega)$, we may write

$$Y(j\Omega) = \frac{K(j\Omega)G(j\Omega)}{1 + K(j\Omega)G(j\Omega)}r(j\Omega)$$  \hspace{1cm} (17)

$$W(j\Omega) = \frac{K(j\Omega)}{1 + K(j\Omega)G(j\Omega)}r(j\Omega).$$  \hspace{1cm} (18)

Dividing (17) by (18) gives

$$\frac{Y(j\Omega)}{W(j\Omega)} = G(j\Omega) = CG_0(j\Omega)$$  \hspace{1cm} (19)

which may be rewritten in the real form as

$$\frac{\|Y(j\Omega)\|}{\|W(j\Omega)\|} = \frac{R_Y}{R_W} = C\|G_0(j\Omega)\| = \tilde{C}.$$  \hspace{1cm} (20)

Since the resonances of the open-loop plant do not change after the tip and sample are engaged, i.e., $\|G_0(j\Omega)\|$ is constant, any variation in $\tilde{C}$ of (20) relates to the changes in parameter $C$ and originates from the LBH variations. Note that $\tilde{C}$ is proportional to the absolute value of the plant dc gain $C$. Thus, whenever actual LBH is lower the obtained $\tilde{C}$ is higher. This is due to the negative sign in (2).

It can be shown that the port at which the exogenous signal is added does not affect (20). However, since $W$ is a small signal, we found that adding $r(j\Omega)$ to the setpoint leads to a better SNR at frequency $\Omega$ at both measured outputs. To this end, we point out that an alternative method for LBH estimation was proposed in the earlier STM literature. The differences
between the two methods and, in particular, the advantages of the method proposed here are detailed in [17].

B. PI Tuning Based on LBH Estimation

It is possible to compensate for LBH variations by adapting the controller gain as

\[
(k_i)_{\text{new}} = k_i \frac{\bar{C}_d}{\bar{C}}
\]

(21)

Here, \( \bar{C} \) is the estimated dc gain of the open-loop system, which is proportional to LBH, and \( \bar{C}_d \) is the desired value for \( \bar{C} \). Both integral and proportional gains are multiplied by the factor \( \bar{C}_d/\bar{C} \). The desired parameter \( \bar{C}_d \) is a user-defined parameter recommended to be selected in the mid-range of observed \( \bar{C} \) variations. Also, we use a saturation block for safety reasons, as shown in Fig. 5.

V. EXPERIMENTAL RESULTS

In this section, first we present the experimental results confirming that the LBH is a variable that depends on local effects. We then go on to present experimental results showing the effect of the self-tuning PI controller on the STM performance and the tip life cycle.

A. LBH Measurements

Fig. 6 displays the estimated parameter \( \bar{C} \) along with RY and RW signals, as shown in Fig. 5, measured while the STM was idle with all user defined parameters fixed. At time \( t \approx 3 \) s controller gain \( k_i \) was increased and subsequently decreased back to its initial value at \( t \approx 22 \) s. Fig. 6 suggests that \( \bar{C} \) is not affected by the controller gains and this agrees with (20).

Fig. 7 shows a plot of \( \bar{C} \) measurements while the STM tip was changing frequently. In this case, the STM tip has two stable states. All control system parameters were fixed during data collection. The STM was engaged, but not scanning. Tip changes are believed to be a major cause of the sudden changes in the LBH.

It was then it was moved back to point A. Substantial changes observed in \( \bar{C} \) suggest that the electronic/chemical properties of the atoms tunneled through at point A are different from those of atoms at point B resulting in different LBH values at the two points. This observation confirms that, while scanning, the LBH can undergo significant variations depending on the chemical composition of the sample surface.

The presented observations confirm that the plant dc gain can take significantly different values, while STM is operating. These variations originate from the tip changes, atomic structure of the sample or any other possible physical source. In addition, these observations suggest the need for continuous tuning of controller gains to prevent instabilities due to dc gain variations.

B. Self-Tuning PI Controller

We conducted several experiments to investigate the stabilizing effect of the PI tuning algorithm proposed in Section IV-B. LBH is measured at \( \Omega = 1 \) kHz with the Lyapunov filter gain set to \( \zeta = 1000 \). In order to show the stabilizing effect of the tuning algorithm, PI gains are intentionally set to a
Fig. 9. PI tuning effects on the STM performance. Topography (left column), \( \tilde{C} \) representing the LBH (middle column), and current error (right column) images for the two cases without PI tuning (top row) and with PI tuning (middle row). Plots at the bottom row show the profiles drawn on the corresponding images above. PI gains are high and the system is close to the stability margin. Surface atomic and electronic structures are visibly different close to the center of the sample due to contamination or previous tip contact. While passing over the low-LBH (high \( \tilde{C} \)) area, the closed-loop system experiences ringing when the PI tuning is inactive. Immediately after the first test, PI tuning is activated and the surface is rescanned. The closed-loop system does not experience ringing with active PI tuning. Ringing appears as artifact in topography image, e.g., area near profiles A and E pointed to by arrows.

Immediately after the first test, we activated the tuning algorithm and rescanned the surface while all other parameters including the initial PI gains were preserved. As shown in the middle row of Fig. 9, the feedback loop remains stable despite large variations in the LBH. Comparison of profiles F and E in Fig. 9 shows that with the PI tuning algorithm the current is better kept constant. Profile D in Fig. 9 shows that \( \tilde{C} \) in the contaminated area is approximately 50% larger than other locations on the surface. This explains the feedback instability in that area with fixed PI gains. While the PI tuning is inactive and the feedback system is ringing, LBH estimation...
Fig. 10. PI tuning effect on the STM performance. The surface is clean with several dangling bonds which represent missing hydrogen atoms. PI gains are high and the surface is scanned successively with PI tuning OFF (top row) and ON (middle row). All other parameters are the same in the two tests. Over the dangling bonds, the estimated $\tilde{C}$ is larger, and this causes ringing when the PI tuning is OFF as evidenced by profile E. When the tuning is active, the feedback system remains stable and no artifact is observed.

We repeated the same experiment on a different sample and with a different tip. Obtained results are shown in Fig. 10. In this experiment, we had a clean hydrogen passivated silicon surface with several dangling bonds representing missing hydrogen atoms that appear as bright dots in the topography images. Over the dangling bonds the LBH is lower and the measured $\tilde{C}$ is higher as shown by profiles C and D in Fig. 10. We used a set of PI gains that put the system close to the stability margin when PI tuning is inactive. While passing over the dangling bonds, the feedback system experiences ringing as shown by profile E in Fig. 10. After the PI tuning is activated, the system operates reliably and produces clean images without artifacts while the initial PI gains are still high.

C. Tip Life Cycle

To perform the experiments reported in Section V-B, we brought the system close to the stability margin by using high PI gains. Although such high gains are not normally
We successively scanned a hydrogen passivated Si surface, while the PI gains and scanning speed were normal, and the tuning algorithm was operating. After collecting 64 images each taking 5 min, we switched OFF the tuning algorithm and continued the successive scanning with the same parameters. Figs. 11 and 12 show one out of four captured images with the PI tuning algorithm and without it, respectively. Fig. 11 shows that, while the tuning algorithm was active, the tip changes did not result in a major crash. However, with the tuning being inactive in Fig. 12, tip changes resulted in formation of undesired patterns on the surface as visible in Fig. 12. These patterns are formed due to some unknown tip-sample interaction that results in the removal of hydrogen atoms from the surface. LBH properties of these regions are similar to dangling bonds. The growth of the formed pattern in the next scans and the final tip crash can be due to the variation of the LBH caused by the tip changes and by the formed patterns.

Fig. 12 images suggest that closed-loop instabilities may originate from tip changes and in turn damage both the tip and the surface. Tip changes are visible in both Figs. 11 and 12 as horizontal sharp color changes. With PI gains fixed in Fig. 12, LBH variations originated from sudden tip changes cause closed-loop ringing and initiate formation of undesired patterns on the surface. LBH is different over the patterned spots which makes the situation worse in successive scans.
VI. CONCLUSION

We analyzed the control system of an STM. Frequency-domain closed-loop system identification tests were conducted to obtain open-loop models of the STM. Our analysis shows that dc gain of the open-loop plant is proportional to the LBH which is a quantum mechanical property of the tip and the sample. The LBH is known to be a variable parameter in STM which depends on many local effects. We showed that the LBH variation can dramatically change the loop gain in the presence of a controller with fixed parameters and this can easily result in closed-loop instability. We proposed an algorithm for online LBH estimation and used the obtained estimation to adaptively tune the PI controller gains. The estimated LBH is also used for generating LBH images which map electronic properties of the surface.

Experimental results confirm that the LBH is a varying parameter, and that the proposed method is effective in enhancing the closed-loop stability. Furthermore, the proposed tuning method allows for safe increase of PI gains that in turn results in higher closed-loop bandwidth and enables high-speed scanning. Further experimental results confirm the effect of the proposed control method on protecting the tip and extending its life cycle by lowering the chance of the tip/sample crash.

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