Fast-acting piezoactuator and digital feedback loop for scanning tunneling microscopes

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The design of a sectional piezoactuator is described, and the principle of operation of a tunnel junction digital stabilization system is given. The total settling time of the system while the least significant section is in operation is 1 μs at 0.01-nm resolution (in the Z direction). The application of the sectional piezoactuator permitted an increase in operating frequency and also eliminated errors caused by the piezoceramics hysteresis. Introduction of a fast-acting ALU as a digital accumulator of regulation errors made it possible to achieve high stability of the loop operation at high operating frequencies. The system suggested can adapt the speed of the loop operation depending on the relief steepness values. The blunting of the tip and sample destruction is avoided because there is a mechanism of smooth approach of the tip to the nominal scanning height.

I. INTRODUCTION

In existing scanning tunneling microscopes (STMs), the piezoactuator and the tunnel junction stabilization system prove to be critical elements when it is necessary to reach high operating speeds. Therefore, for a fast-acting system it is necessary to develop a piezoactuator with short-time response and a stabilization system with minimum control signal delay in the feedback loop.

Further miniaturization up to the size of an integral drive is one of the methods of creating a fast-acting piezoactuator. This allows one to reduce its inertial mass and to decrease the time of oscillation propagation. The operation range of such actuators is very small (several nanometers) and in order to achieve the movement required for the STM tip to approach the sample surface, it is necessary to use intermediate stages coordinating the transition from micrometer to nanometer scales.

The main requirement for a STM control system is accuracy that ensures atomic resolution for the tool. The requirement that the system is fast acting, as a rule, comes into contradiction with the requirement of accuracy. The system offered is an attempt to eliminate this contradiction.

The control system may be both analog and digital. Theoretically, an analog system can provide the highest degree of fast action, while a digital system allows one to create more complicated control algorithms. It can be self-tested, possesses a high insusceptibility to electrical inductive noise, and easily interfaces with a microcomputer.

II. DESCRIPTION OF THE SYSTEM

The digital servosystem under consideration (Fig. 1) is intended for STM tunnel junction stabilization. It uses a sectional actuator as the final executing element. The system consists of AMP tunnel current amplifier; ADC, converting the tunnel current into the digital code; ALU, carrying out the integrator function and electromechanical DAC, converting the code into the displacement in the Z direction (other directions are not considered). The electromechanical DAC operation principle is based on connecting the reference voltages set to the actuator sections by means of COM commutator depending upon the RG_AC register-accumulator bit state. This set is generated by REF_PRC_ACT source.

A. Actuator

A sectional design was chosen for the fast-acting piezoactuator (similar to the one described in Ref. 1). However in order to achieve higher speeds of movement the actuator sections are made equal in length, but with different control voltages changing from one section to another as

$$u_n=u_0\cdot 2^n, \tag{1}$$

where $n=0...7$ is the actuator section number.

This power law is necessary for creating the digital feedback loop and, in particular, for creating the electromechanical digital-to-analog converter. Figure 2 presents a manipulator with three stages: coarse, mid, and precise. The control voltage values for the actuator, which operates using the transverse piezoeffect can be determined in the following way. For the initial piezoactuator length l of 20 mm, the sensitivity of the piezoceramic design S is 10 nm/V, therefore for the section length l_{sec}, which is equal to 1 mm, S_{sec} sensitivity can be given by the following ratio[2,3]

$$S_{sec}=\frac{S}{l/l_{sec}}=0.5\ \text{nm/V}. \tag{2}$$

Resolution of the precise actuator when the sections are key controlled is equivalent to the movement range of the least significant section d_0 and must be equal to 0.01 nm, then the movement d_n of the other sections can be found from the following equation

$$d_n=d_0\cdot 2^n, \tag{3}$$

where $n=0...7$. Generally, the value of the actuator movement d, when U control voltage is applied, is

$$d=S\cdot U. \tag{4}$$

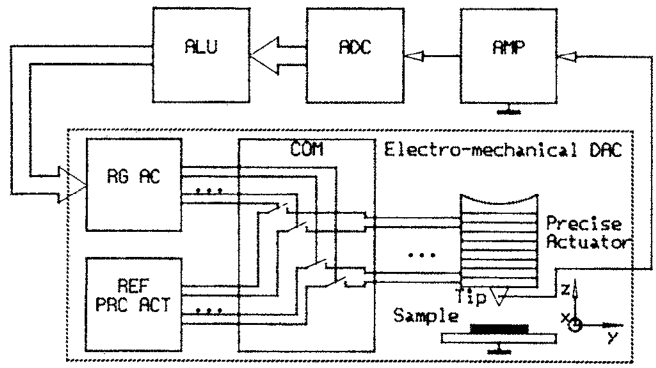

FIG. 1. Simplified feedback loop functional flow chart.

Then, weight voltage u_0 which is to be applied to the least significant section, is calculated as

$$u_0 = \frac{d_0}{S_{\text{sec}}} = 0.02 \text{ V}, \tag{5}$$

thus, weight voltages u_n for the other sections can be calculated from Eq. (1). The calculation results are given in Table I.

The tip-positioning accuracy depends on the accuracy provided by the actuator and is ensured by the section fabrication precision, ceramics homogeneity, and the constancy of weight voltage.

The manipulator mid-stage length is

$$l_{\text{mid}} = l - l_{\text{prc}} = 12 \text{ mm}. \tag{6}$$

Then the sensitivity S_{mid} from formula (2) is 6 nm/V. The maximum voltage $U_{\max}$ applied to the mid actuator is limited by the ceramics saturation process and is 200 V. Then, the voltage that corresponds the minimum step of the mid actuator is defined as

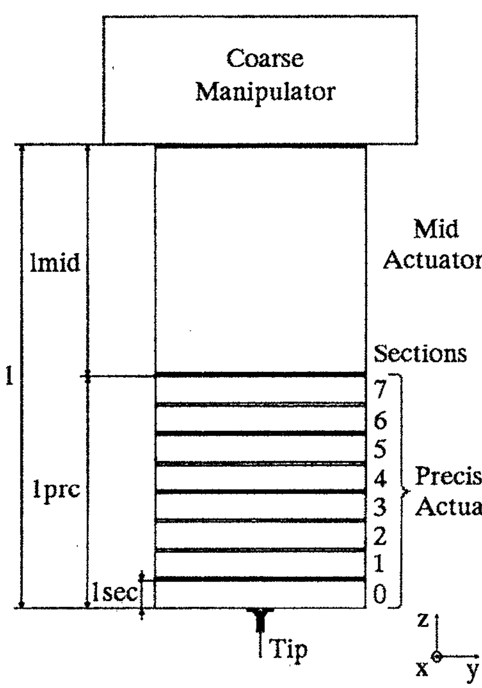

FIG. 2. Manipulator.

TABLE I. Calculation results for the sectional actuator.

n (sections)	d_n (nm)	l_{sec} (mm)	u_n (V)
0	0.01	1	0.02
1	0.02	1	0.04
2	0.04	1	0.08
3	0.08	1	0.16
4	0.16	1	0.32
5	0.32	1	0.64
6	0.64	1	1.28
7	1.28	1	2.56
	$\Sigma d_n = 2.55$	$\Sigma l_{\text{sec}} = 8$	

$$U_{\text{step}} = U_{\max}/2^n \approx 48.8 \text{ mV}, \tag{7}$$

where $n = 12$ is the capacity of DAC controlling the manipulator mid stage. Then, from Eq. (4), the step is

$$d_{\text{step}}^{\text{mid}} = S_{\text{mid}} \cdot U_{\text{step}} \approx 0.3 \text{ nm}. \tag{8}$$

The mid actuator movement range is

$$d_{\text{mid}} = S_{\text{mid}} \cdot U_{\max} = 1200 \text{ nm}. \tag{9}$$

Thus, the three-stage system is described, the coarser stage step must not be greater than the more precise stage operating range, i.e.,

$$\sum_{n=0}^{7} d_n > d_{\text{step}}^{\text{mid}}, \quad d_{\text{mid}} > d_{\text{step}}^{\text{coarse}}. \tag{10}$$

The coarse manipulator control is not considered in the present article. It meets the requirement to provide a step not greater than 1200 nm, which can be obtained using a screw pair, stepper motors, or other devices.[4–6]

B. Feedback loop

Let us first consider the operation of the smooth tip approach scheme to the nominal scanning height. This scheme (Fig. 3) includes RG_APR register, DAC_APR digital-to-analog converter, and FET field-effect transistor and is intended for the smooth approach of the tip to the sample surface up to the height $h_{\text{nom}} = 0.1 \ldots 1$ nm (*A-C* section in Fig. 4), which allows one to avoid abrupt rushes of the servo system and responding rushes of the actuator with the tip on it at the moment the system starts, as well as at the moments recognized by the state definition scheme as "Failure."

The approach scheme works in the following way. The FET serves as an electrically controlled resistor $R1$ (source-drain) in the measuring bridge arm. At first, the FET is pinched-off, because the constant bias gate-source voltage is applied. The FET resistance is high and reaches dozens of MΩ; the resistance of $R2$ (tunnel junction) is also high because the tip is rather far from the sample surface. The servo system tries to reduce the error to zero. After that the program is initiated and sends a linearly

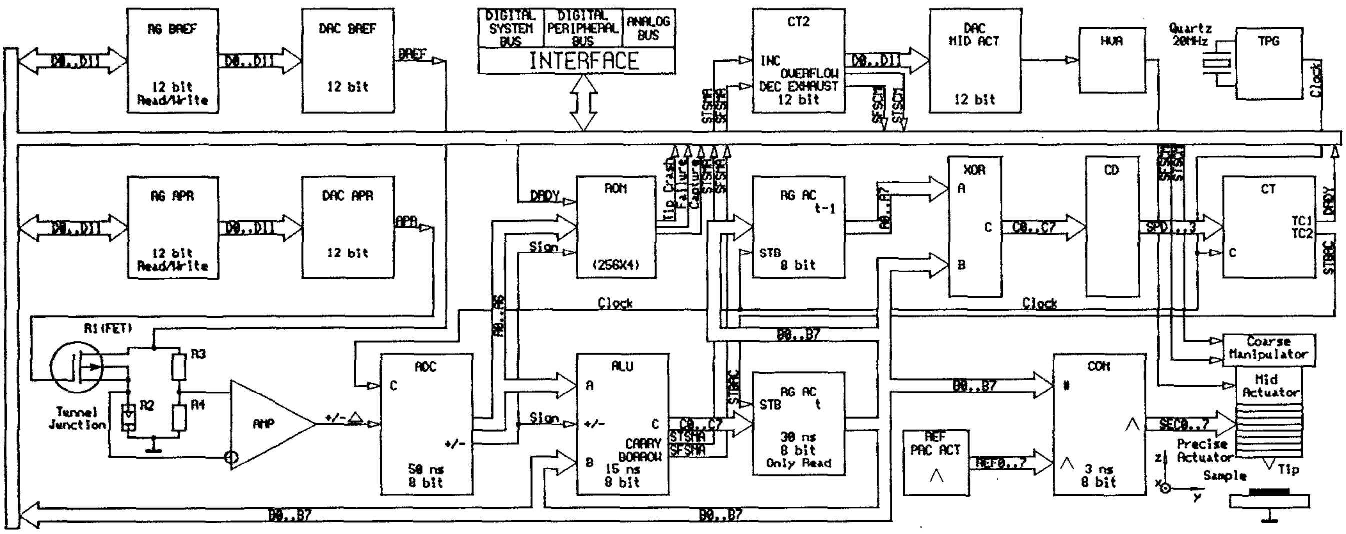

FIG. 3. Feedback loop functional flow chart.

increasing code into RG_APR. Then this code acts on DAC_APR, which generates the opening "APR" voltage for the FET reducing its source-drain resistance. At this moment the feedback loop attempts to compensate slowly increasing difference between $R1$ and $R2$. After the nominal height h_{nom} is reached the register fixes the last code, which corresponds to the digital form of h_{nom} in the control system. After that the return from the interrupt to the main program is executed. In other words, during the approach phase, the height has some floating value, which then approaches the h_{nom} operating value. The method described allows one to set different scanning heights using software.

Provided an abruptly increased imbalance occurs in the STM control system for some reason (vibration, shocks, electromagnetic noise, etc.) and its value becomes greater than a certain fixed threshold (code), then the state definition scheme, after its identification, generates a "Failure" signal. This signal causes a hardware interrupt, after which the system will produce the action to return the tip to h_{nom} as described above.

Let us describe now the digital servo system operation. Selected and amplified by the AMP differential amplifier, the control system error signal "$\pm\Delta$" is sent to the fast-acting ADC. This ADC is intended for fast converting the "$\pm\Delta$" analog value into the 8-bit digital equivalent, where the high-order bit is the sign bit. "$A0..A6$" code and "Sign" signal simultaneously get into the state definition scheme and into the fast-acting ALU from the output of the fast acting ADC.

The state definition scheme consists of a ROM and is intended for identifying and displaying the three feedback loop states depending upon the error signal value and its sign (see Fig. 5), namely: "Tip Crash," "Failure," "Capture." The "Tip Crash" state is set if the tip touches down on the surface. In this case, a high-priority hardware interrupt is initiated; according to its program, the tip is parked and the whole work is halted. The "Failure" state means a failure of the surface relief acquisition. In this case, a middle-priority hardware interrupt is generated, which activates the mode of smooth tip approach to the nominal height. The "Capture" state means the "capture" of the surface for acquisition. In accordance with the sig-

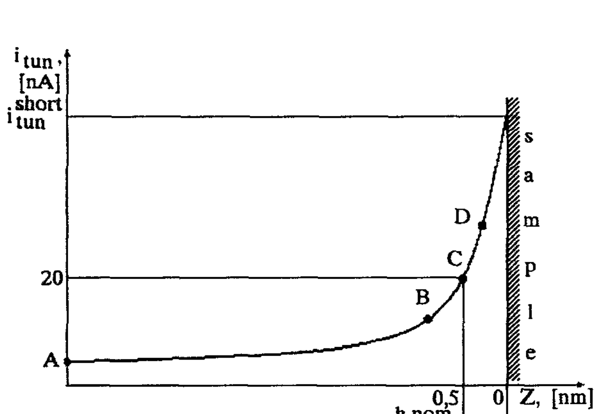

FIG. 4. Tunnel current vs the tunnel junction value.

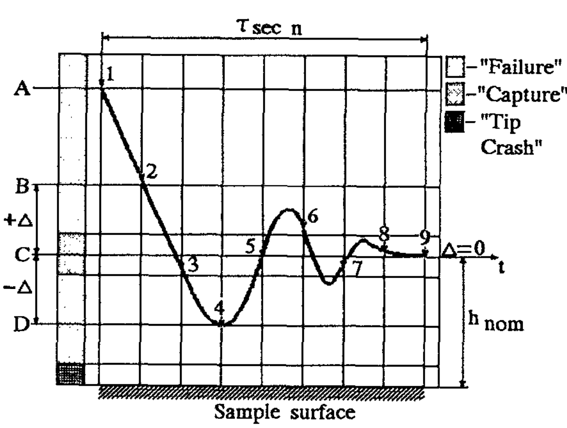

FIG. 5. Formation of the $\pm\Delta$ displacement. Ranges of states "Tip Crash," "Failure," and "Capture." Transitional process of the actuator.

nal, the least-priority hardware interrupt is generated. Its processing program reads the contents of the RG_AC_t register which stores the information of the current tip height in the microcomputer memory. Then a signal is generated, permitting the scanning scheme to make a step in the sample plane.

For each of the three states recognized by the system, a certain code interval corresponds, in which the state is active. The intervals are connected without overlapping and gaps, which excludes ambiguity and uncertainty of the current state of the regulation system. One can note that the code interval of the "Capture" state corresponds to the servo system accuracy.

As the precise actuator is not an absolutely rigid body and is therefore characterized by some mechanical transient processes, the measuring system, in passing, for instance, from the "Failure" state (pos. 1, Fig. 5) to the "Capture" (pos. 9), will display the error states "Capture" (pos. 3,5) and "Failure" (pos. 4,6). Therefore, for the error signals elimination during the displacement produced by the actuator sections, it is necessary to fix the "Failure" and "Capture" states, which are strobed by the "DRDY" (Data Ready) signal synchronizing the "slow" actuator section operation with the fast operation of the loop electronic scheme.

The fast-acting ALU is intended for carrying out the accumulator function for the serial values of displacement and is equivalent to an integrator in an analog servo system. Without ALU the system would operate with nonattenuated oscillations. According to the "STBAC" (Strobe to Accumulator) signal generated by the synchronization scheme the current displacement is added to (or subtracted from, depending on its sign) the contents of the RG_AC_t accumulator register, which stores the operation result. One can note that its contents are the sum of all the previous displacement values (taking the sign into consideration). The sum obtained in the form of a digital code is sent to the COM commutator. This commutator applies the appropriate weight voltages to the precise actuator sections in accordance with the state of its bits. The weight voltages are generated by the REF_PRC_ACT scheme.

Thus, the RG_AC_t, the COM, the REF_PRC_ACT scheme, and the sectional actuator itself compose an electromechanical DAC scheme. One can note that the described key control principle for the precise actuator allows one to eliminate the ambiguity from the servo system contour caused by the piezoceramics hysteresis.

At some moments the digital loop ALU will be overflowed or exhausted. For instance, it happens when the heights range along the surface scanned appears to be greater than the movement range of the precise actuator or because of small displacement accumulation during a prolonged descent or ascent.

In case ALU overflows, the following sequence of operations is initiated in the system: zero voltage is applied to all the actuator sections and the actuator squeezes to its initial length. This is necessary in order to prevent possible collision with the surface. At the same moment, the "STSMA" (Step to Surface by Mid Actuator) carry signal gets into the CT2 reversible counter and increments its contents; as a result the mid actuator makes a step towards the surface. A large displacement is produced and the state definition scheme will set the "Failure" state, which signal initiates the hardware interrupt request. The program of this interrupt controls the scheme of the smooth tip approach to the nominal scanning height till the "Capture" state is set.

The moment ALU is exhausted the servo system acts in the reverse order, i.e., the counter decrements, its contents, and the mid actuator make a step away from the surface; the precise actuator state is not important.

Thus, while approaching the nominal height the servo system "checks" the way ahead using the precise actuator. Provided this way proves to be longer than its range allows, the mid actuator will make a step (it was in a fixed state before this).

During the prolonged descent or ascent, and when the tip approaches the nominal height, the CT2 counter (as ALU) may also be overflowed or exhausted, therefore, to control the coarse manipulator, the "STSCM" (Step To Surface by Coarse Manipulator) and "SFSCM" (Step From Surface by Coarse Manipulator) interface signals are used. As the time constant of the coarse manipulator is large, for synchronizing the process the feedback loop scheme waits for the answer signal from the coarse manipulator control scheme. Then the digital code stored in the counter gets into the DAC_MID_ACT. From its output, the analog signal passes into the HVA high-voltage amplifier and then to the mid actuator. "STSMA," "SFSMA," "STSCM," and "SFSCM" are read into the microcomputer memory together with the RG_AC_t contents and participate in the surface relief reconstruction.

As the time constant of the sectional actuator is larger than the time constant of the feedback loop, and ALU is an asynchronous circuit and continues to add the "slowly" changing displacement value, it is necessary to rigidly synchronize the RG_AC_t operation for eliminating large overshoots and parasitic oscillations. This register locks the data, fed to the precise actuator until the transient process is over. The scheme consisting of RG_AC_{t-1} register, XOR element, CD coder, and CT counter is used to achieve this kind of synchronization.

Besides the function described above, the synchronization scheme optimizes the feedback loop speed depending on the displacement value, which, in its turn, is determined by the steepness of the surface relief change. The precise actuator is partitioned into equal sections; therefore the time response of an arbitrary section n is

$$\tau_{\sec\ n}=(n+1)\cdot\tau_{\sec\ 0}, \tag{11}$$

where $n=0...7$; $\tau_{\sec\ 0}$ is the time of acoustic wave propagation through the least significant section, which is ~ 250 ns.[7] In accordance with the formula, the time response to the control signal of the section nearest to the tip is less than for the others. Therefore, if the state of the sections more distant from the tip does not change when the system is in operation, it is possible to increase the loop operating speed. This can be done in the following way. At the $t-1$

moment, the contents of the RG_AC$_t$ register are stored in RG_AC$_{t-1}$; then at t time, XOR executes the bit-oriented operation "exclusive-OR" upon the contents of the two registers and thus determines the bits which in the course of transition from $t-1$ time to t time change their state from 0 to 1 or vice versa. Then, the CD priority coder extracts the "SPD 1..3" code, corresponding to above state change for the farthest from the tip actuator section. Then, this code is being written into the CT programmable counter, changing the division coefficient and hence, output frequency, which defines the necessary delay $\tau_{\mathrm{sec}\ n}$ between the current loop state and that will follow.

Thus, the system described appears to be adaptable. Its operation speed depends on the relief roughness values. For instance, if they are large, the loop reduces the speed, and vice versa—if they are small, it works with the maximum performance.

Let us describe the feedback loop components performing auxiliary functions. The reference voltage measuring bridge setter is assembled on the RG_BREF register and the DAC_BREF. The setter is intended to generate the "BREF" reference voltage, applied to the measuring bridge.

The TPG timing-pulse generator is intended to generate stable high-frequency impulses, which feed the fast-acting ADC and the synchronization scheme.

The interface scheme allows one to program the measuring bridge reference voltage setter scheme and the scheme of smooth tip approach to the nominal scanning height, to read the information of the surface relief and to organize the data exchange with the microcomputer by means of interrupts or direct memory access.

III. DISCUSSION

Among the previously suggested digital fast-acting systems there following previous work should be mentioned.

Morgan and Stupian[8] use a digital signal processor (DSP) in a feedback loop, realizing a PID regulator. The loop can be set to respond to a frequency up to the order of tens of kHz. The advantages afforded by the DSP include greater flexibility in the choice of algorithms and greater ease of control of loop. But this speed is not enough.

Robinson *et al.*[9] introduced a digital integrator and scan generator coupled with dynamic scanning. The scheme described uses a similar approach in solving the problem and consists of two comparators (similar to state definition scheme in our system), which set an operational window about the tunnel current. The integrator count rate is controlled by a voltage-controlled oscillator, whose output frequency is determined by the rectified difference between the tunnel current and the midpoint of the comparator window (similar to ADC-ALU-RG_AC chain). The main difference, comparing our systems, is the transition from the monolithic construction of the precise actuator to a sectional one, that, besides the other advantages, excludes the use of a DAC and, therefore, an additional delay in feedback. Besides, our system has a clear hierarchical principle of dividing the manipulator into three stages, having its own range, step value, speed, and action priority, which results in an increase of the system performance.

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