Compact mobilized and low-cost scanning tunneling microscope for educational use

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We developed a mobile, compact and easy-to-use educational STM device with dimensions of 10 x 15 x 20 cm. It is a completely independent unit and, except for a PC, does not require any additional hardware. The computer interface does not require expansion or sampling cards, but instead is based on the standard USB or EPP ports. In this way, the system may also be based on the recent popularity of mobile computers. The most advanced technology was used; this enables miniaturizing and lowering the price of the system to a level suitable for the purchase by educational institutions for the experience of discovering and learning about nano-science.

Keywords STM; Educational; SPM

1. Introduction

The invention of the Scanning Tunneling Microscope (STM) [1] triggered the development of a family of high-resolution microscopes called Scanning Probe Microscopes (SPM) [2]. Among SPMs techniques we find the Atomic Force Microscope (AFM) [3], the Magnetic Force Microscope (MFM) and the Scanning Near-Field Optical Microscope (SNOM) [4,5]. All SPMs use fine piezoelectric transducers controlled by feedback mechanisms to scan samples with a very sharp tip at very short distances. The difference between the various techniques is that each type maps different characteristics of the sample by using its own unique interaction mechanism between the tip and the sample.

The Scanning Tunneling Microscope (STM) is widely used in both industrial and fundamental research to obtain atomic-scale images of conductors and semiconductors metal surfaces. It provides a three-dimensional profile (and other local attributes) of the surface, which is very useful for characterizing surface roughness, observing surface defects, and determining the size and conformation of molecules and aggregates on the surface. In addition to probing surfaces and molecules, STMs are also used to modify surfaces and manipulate individual atoms. The STM functions by detecting small currents flowing between the microscope tip and the observed sample (the current flows due to quantum mechanical tunneling). Such a microscope is vital for physics and chemistry laboratories in Schools and in Universities. Children of all ages would be able to absorb science, in particular nano-technology, by experiencing the ultimate method – visually.

Currently, however, major drawbacks prevent this scenario from happening. First of all, only some of the educational institutes can afford the high cost of STM. Secondly, it is too large and too difficult to use and move around. Moreover, the current interface of the STM is not sufficiently user-friendly, and even proves to be intimidating for some. This may estrange children from nanotechnology, instead of connecting them to it, as is one of the purposes of bringing STMs into schools.

We developed a mobile, compact and easy-to-use educational STM device with dimensions of 20 x 15 x 10 cm. It is a completely independent unit and the only additional hardware required is a PC. The computer interface does not require expansion or sampling cards, but instead is based on the standard USB or EPP ports. In this way, the system may also be based on the recently popularized mobile computers. The most advanced technology was used in order to realize the electronics in the system – FPGA and CPLD programmable logic, tiny micro-controller, the latest high voltage amplifiers, etc. The system is characterized by its simple operation which is based entirely on the monitoring program's GUI. The program does not include the unique use of a certain operating system, so it may be operated on different platforms. This enables miniaturizing and lowering the price of the system to a level suitable for laboratories with small and intermediate budgets.

The extremely low price of the entire system (aside from a computer) will enable educational institutions, other than academic research laboratories, (laboratories for undergraduates in colleges, universities and even high schools) to purchase the system and experience an educational program about nano-science.

2. The Structure of the SPM System

In 1880, Jacques and Pierre Curie discovered that pressure applied to quartz crystals produces an electrical voltage in the crystal; they termed this phenomenon "piezoelectric effect". Later, they found that voltage applied to crystals of this type causes deformation in the material; this phenomenon was termed "opposite piezoelectric effect". Today, piezoelectric materials constitute the basis of numerous applications including sensors, ultrasonic systems, musical instruments and more. The ability to cause very small deformations, in the scope of nanometers, by applying voltage

(10 nanometers per volt) has made piezoelectric crystals a central component of SPM systems. These crystals play a part in motion, inspection, and scanning elements of the SPM, which is generally comprised of the following elements:

- A mechanical head which serves to scan surfaces and possesses the ability to move on three axes (X, Y, and Z), at a very high resolution, such that the X and Y axes are on the plane of the surface and the Z axis is perpendicular to it.
- A course approach mechanism in the Z direction that quickly brings the probe closer to the surface.
- A Proportional Integral Differential (PID) electronic controller in the feedback loop that stabilizes the tip next to the surface and moves it in the Z direction.
- A scanning controller that moves the head in the X-Y direction.
- A mechanism to dampen vibrations and provide thermal and acoustic isolation.
- A computer, evaluation software, and processing software.

Each one of the above components may be implemented in different technologies and with a different technique, and each one, of course, possesses advantages and disadvantages. In planning systems, applications and work methods must be taken into account, and decisions about each one of the elements need to be made accordingly. A central element in planning is the course approach mechanism (including the evaluation software, if it exists). This element will determine the life span of the probe and the surface, and the approach speed of the tip to the surface. The second most important element is the mechanical head that determines the physical size, the stability, the method of replacing the probe and possibilities for upgrading. The controllers will determine the scanning range, the dynamic range, the sensitivity, the signal-to-noise ratio and the complexity of the software. The dampening and isolation system will influence the mobility of the system, its general size and the environmental conditions in which the system will operate properly. For computation purposes, there is a marginal influence on the system and a large influence on convenience for the user.

3. The System Elements in Detail

3.1 Mechanical Head (Junction)

The mechanical design of the head is highly dependent upon the course approach mechanism, part of which serves as part of the head. A visual description of the typical mechanical head appears in Figure 1. The 3-D scanning mechanism is comprised of 2 piezoelectric tubes that are connected to one another on a concentric axis and move the probe in XYZ directions. An internal tube, covered by nickel electrodes on both its inner and outer surfaces, serves to move the tip in Z direction. An external tube, covered by nickel electrodes that are divided into four lengthwise quadrants on the outer surface, move the probe in the XY direction. The tubes are assembled one inside the other along a mutual axis, and are connected using epoxy glue. Such a structure improves the thermal stability of the junction by compensating for the difference in the lengthening between the two tubes [6]. The probe (a platinum wire) that moves close to the surface is attached firmly to the internal piezoelectric tube.

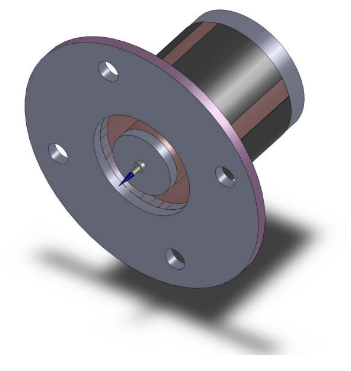

Figure 1 The 3-D scanning mechanism is comprised of 2 piezoelectric tubes that are connected to one another on a concentric axis and move the head in XYZ directions.

The mechanism that includes the tip and the crystals serves as one half of the STM junction. The second half of the STM junction, which carries the scanning surface, includes the course approach mechanism (explained below).

3.2 Course Approach Mechanism

One important part of the SPM, that affects its design and performance extensively, is the course approach mechanism. This mechanism is used to bring the tip from a setup position, "far away" from the sample (a few millimeters), to a scanning position, "very close" to the sample (< 1 μm), in fast sub-micron steps. On the one hand, the approach velocity, which is determined by the step size and rate, should be limited in order to protect the tip from any damage. On the other hand, this velocity should be fast enough in order to avoid a long approach time.

All of the modern approach mechanisms are based primarily on piezoelectric motors that may be classified into two general categories: "piezo stepping devices" and "piezo inertial sliders". These piezo-steppers and inertial sliders motors can provide nanometer steps over a macroscopic range of travel.

A piezo-stepping device is able to produce a discrete step by clamping its rear leg to the support surface, expanding the piezo-body, clamping its front leg to the surface and releasing its rear leg, contracting its body, and continuing in this manner. Clamping is achieved by various methods such as: electro-static attraction [1], friction [7,8], or Burleigh Instrument's commercial inchworm [9]. The driving voltage for the piezo stepping devices are digital signals at high voltages of hundreds of volts (at the very least, three independent channels).

The piezo inertial sliders [10,11,12,13] are similar to piezo stepping devices in that they also utilize expansions and contractions of the piezo-electric crystals to create a quick series of sub-micron steps. In contrast, piezo inertial sliders do not possess unique clamping mechanisms and they utilize, wisely, friction for this purpose. Through acceleration and deceleration of the body in an asymmetrical manner, it is possible to achieve different forces in different directions, such that the force in one direction overcomes the friction and allows sliding, while in the opposite direction, the force does not overcome the friction and does not slide. In this way, the body will move in the direction of the force that is overcoming the sliding, at the rate of the acceleration change, and in the steps size of the displacement amplitude. The driving voltages for the piezo inertial sliders are analog signals at high voltages of hundreds of volts (one channel for each axis).

The main difficulty in designing the inertial sliding mechanism is the heavy reliance on friction coefficients that are difficult to predict in advance (especially their change over time) and the creation of analog signals at a high voltage [14]. The cost of the piezo-electric motors is very high (from hundreds to thousands of dollars), and therefore, their integration in inexpensive systems is not possible. An inexpensive alternative (under $50) for these motors is a stepper motor with a high transmission ratio gear that allows sub-micron steps. In implementing the course approach mechanism, we used a small, inexpensive stepper motor, possessing 48 steps per revolution and a gear with a transmission ratio of 75:1, attached to a fine-threaded screw with 80 revolutions per inch. As it is easy to calculate, in such a system the size of the step is around 100 nanometers, and the cost of the system is under $50. Figure 2 shows the mechanical system in its entirety. A stainless steel plate with a thickness of 20 mm holds the scanning head described in the previous section. Above the plate, moving on the axis, is an arm that contains the scanned surface. The stepper motor, which is connected to the bottom of the plate, moves the arm up and down and determines the distance between the probe and the surface. On the right side, we see the space in which the current preamplifier is assembled. The preamplifier is connected on one side to the probe, and on the other, like all electric terminals, to the connector on the front, that connects to the controller.

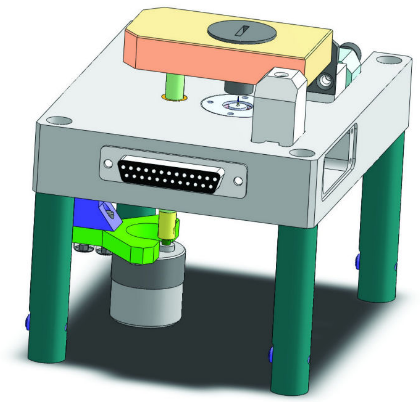

Figure 2 The mechanical system in its entirety: the arm that contains the scanned surface, the scanning head, and the stepper motor with the screw. On the right side, we see the space in which the current preamplifier is assembled. The preamplifier is connected on one side to the probe, and on the other, like all electric terminals, to the connector on the front, that connects to the controller.

3.3 Feedback and Scanning Controllers

The function of the PID feedback controller is to stabilize the probe beside the surface, while keeping the tunneling current, as determined by the user, constant. The system's response and stability will be dependent upon all of the parameters comprising the closed loop between the current preamplifier and crystal that controls the probe. Generally, this loop includes: a preamplifier, a linear rectifier, a PID compensator, and a high voltage amplifier. The control is implemented in one of the two following ways: Analog – operational amplifiers and passive networks, or Digital – a unique DSP card that runs a PID algorithm in the software. The scanning unit shifts the probe on the plane parallel to the surface, while the closed loop feedback controller stabilizes the probe, ensuring that it remains in one of two states: at a constant distance from the surface or with a constant current in the junction.

The XY scanning crystal is divided into four quadrants, making up two pairs. In each pair, made up of two opposing quadrants, the electrodes accept similar voltages with opposite polarities. Such a voltage causes the deformation of the crystal in the direction of X and/or Y. The electronic scanning controller is implemented with computerized techniques, using a Digital-to-Analog Converter (DAC), which changes the supplied voltage according to time, by computer commands. The referenced voltage and bit resolution of the converter determine the scanning range and the level of separation.

3.4 Mechanical, Acoustic, and Thermal Isolation

Without isolation components, atomic resolution is not possible in SPM systems. As is well known, in every environment, there are mechanical noise components that stem from the movement of the building. These noises have a characteristic spectrum, primarily in the frequencies in which heavy instruments operate. The noise passes through a structure and permeates the system all the way to the mechanical head (the SPM junction). Since the system's signals are in the scope of nanometers, such movements must be prevented from reaching the junction. The attachment between the probe and the surface is rigid and is characterized by a resonant frequency of thousands of hertz. Our goal is to block frequencies in this spectrum with an appropriate filter which blocks a high frequency above 1 Hz. A typical isolation system has a series of Low Past Filters (LPF) that possess very low resonant frequencies. The first level is comprised of a heavy granite plate placed on coarse springs; it is characterized by a resonance of 2-5 Hz and serves as a basis for the system. The second level is made up of an aluminum plate, on which the mechanical head is placed, and hangs from 4 rubber bands, which together have a resonance of less than 1 Hz. Acoustic sounds arrive at the junction in the form of vibrations that operate similarly to mechanical noise. Temperature changes during the scanning cause a drift on the XYZ axes and distorts the picture.

4. The Electronic Controller

In an effort to make the electronic controller as small and as inexpensive as possible, we chose to use the personal computer in every parameter possible. The block diagram of the controller is described in Figure 3. The computer is connected to the system through the LOGIC block, which includes a CPLD (designed in VHDL) that implements all of the communication and logic aspects of the system. This block receives commands from the computer and sends them to all of the relevant system components: the analog-digital converter, the digital-analog converter, the micro-controller, and the Z-axis controller. The tunneling current, which comes from the current preamplifier located in the mechanical head [15,16], is amplified, filtered and rectified by the two analog blocks, FILTER and RECTAMP. The PID block implements the Z-axis controller in an analog manner. The PID coefficients are determined by the digital potentiometers that receive their value from the computer. The BUFFER block receives analog voltages from the DAC and PID blocks, including the XYZ voltages. The X and Y voltages are supplied in two separate components: a scanning value and an offset value. Using this method, it is possible, through different gain, to achieve high resolution scan using a 14-bit converter. Every five voltages at the outlet of the BUFFER are transferred to the HV-AMP block, which uses inexpensive high voltage amplifiers (PA240) to amplify the analog voltages from levels of 10 volts to levels of 150 volts, a voltage level suited to driving the crystals to our desired range. The ADC block uses a 12-bit 8-channel inexpensive analog-to-digital converter (MAX197) for sampling the current value, the Z value and additional control values. The sampled values are transferred directly to the computer's memory and are not saved on the controller. The DAC block uses a 14-bit 8-channel digital-to-analog converter (AD7841) to supply voltage to the junction by means of the BIAS block, to supply the reference value to the tunneling current, and to supply scanning and offset voltages to the XY axes.

In addition to a CPLD, we use a tiny micro-controller (PIC16) to control the stepper motor of the course approach mechanism, to set the potentiometer values of the PID unit using the SPI protocol and to save the system values in the non-volatile memory (E^2PROM). In the case of course approach, a controller that receives a command from the computer through the CPLD starts to operate independently by sending pulses, at a constant programmable rate, to the stepper motor. The motor brings the surface closer to the probe until a small current is detected (10 pA). With the detection of a current, through the TUNNEL unit, the controller independently stops the motor's operations immediately and informs the computer.

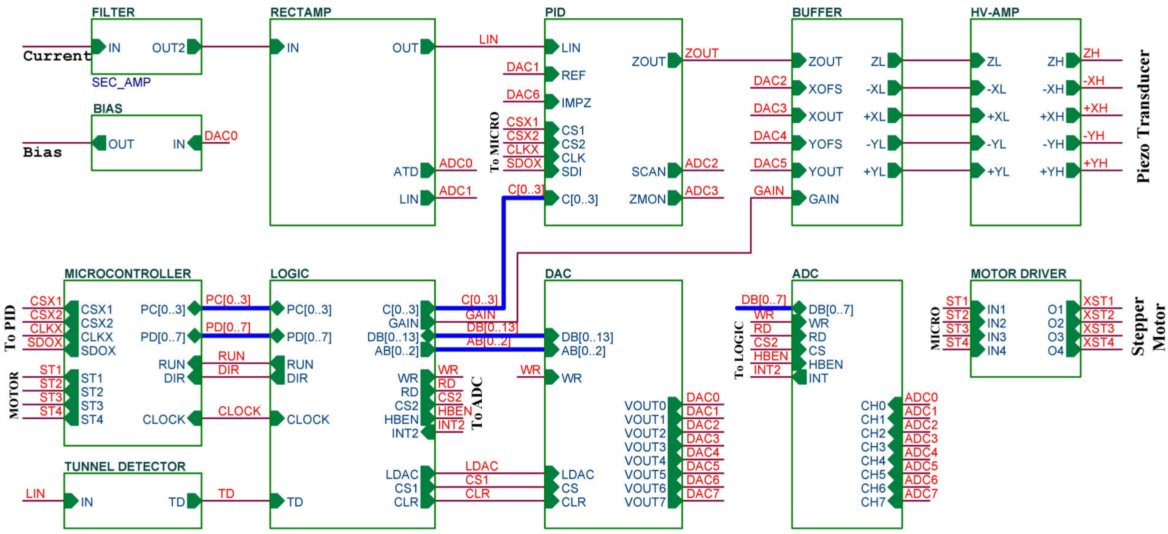

Figure 3 The block diagram of the controller. The computer is connected to the system through the LOGIC block, which includes a CPLD (designed in VHDL) that implements all of the communication and logic aspects of the system.

The power supplies of the system include five different supplies: +5V for the digital part and for driving the motor, ±15V for the analog part, and ±160V for the high voltage amplifiers (for driving the Piezoelectric crystals). Because noise is a very important issue in this system, all of the power supplies are linear. In consideration of size and cost, we chose to plan the power supplies ourselves and implement them as part of the electronic controller. Due to the fact that this system consumes a low current, it was possible to use small transformers designed for assembly on PCB.

Figure 4 displays the electronic controller, whose dimensions are 10cm by 15cm by 20cm. The bottom PCB contains the power supplies and the transformers. The top PCB contains the remainder of the system components described above. As is evident, the layout is divided into five portions: a digital region, including the CPLD and the controller; a mixed signal region including the converters; an analog region including the amplifiers and the PID controller; a high voltage region including the five voltage channels for the Piezoelectric crystals; and a region of relatively high currents for driving the stepper motor.

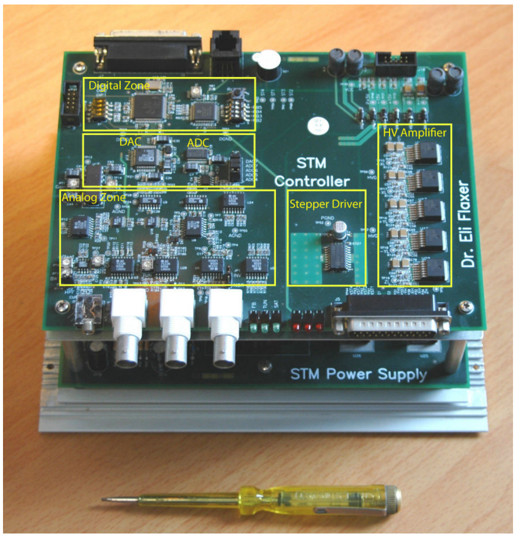

Figure 4 The electronic controller, whose dimensions are 10cm by 15cm by 20cm. The bottom PCB contains the five power supplies. The top PCB contains the remainder of the system components. The layout is divided into five portions: a digital region, including the CPLD and the controller; a mixed signal region including the converters; an analog region including the amplifiers and the PID controller; a high voltage region including the five voltage channels for the Piezoelectric crystals; and a region of relatively high currents for driving the stepper motor.

5. The Software

As stated above, a large part of the operation was transferred to software. In addition to the system's controlling operations, the software executes the scanning process, data acquisition and signal processing, and chooses the operation mode: a constant current or constant height. In the design of such an operation we can eliminate the necessity for a strong processor and a large memory.

We used the National Instrument Lab Windows/CVI [17] environment to write the software and the drivers. This environment was chosen because it has several distinct advantages: 1) A complete transparency to the programmer who programs in C, as there is no need to write any source code line to produce this GUI. 2) Full compatibility with ANSI C, and compatibility with C++ using an external compiler like visual C. 3) A wide support range in addressing many hardware devices and instruments. 4) Low-level support drivers for I/O port addressing. 5) A wide range of libraries for analysis, communication, and more.

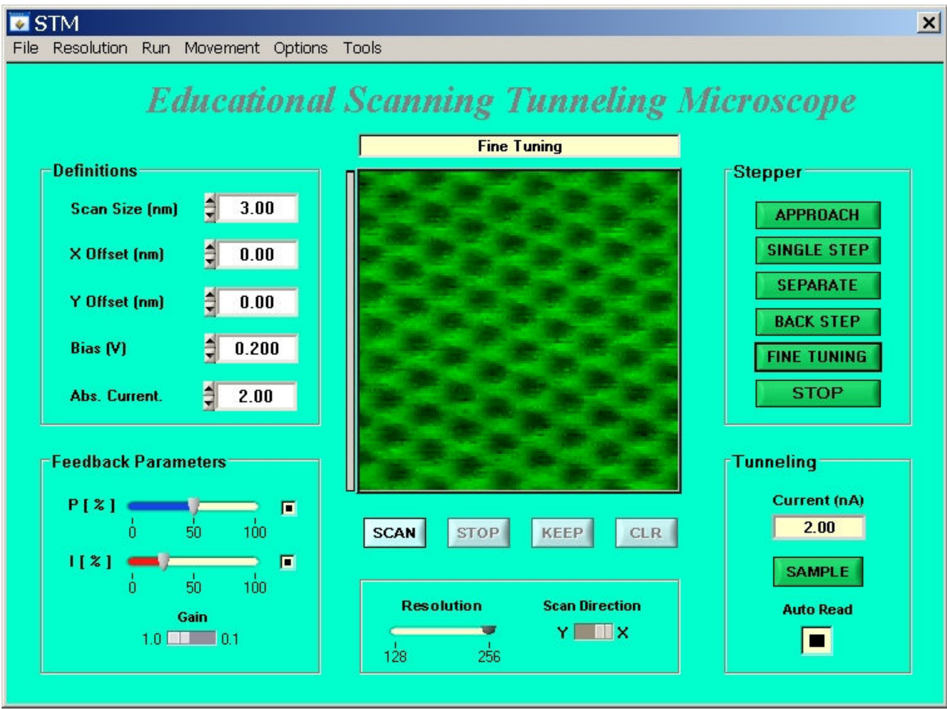

Figure 5 The central window of the control software – Written by National Instrument Lab Windows/CVI environment. In the centre of the screen - a raw data of graphite picture (3nm by 3nm in size) without image processing, is shown. Additionally, the software has options of image processing, displaying cross sections of the XY plane and displaying a 3-D picture.

Figure 5 presents the central window of the control software [18]. The software is very simple to operate as all of the operations can be executed through this window. The user can choose between two scanning resolutions: 128 or 256 pixels per picture. The buttons on the right side (Stepper) belong to the course approach mechanism and allow control of the stepper motor. Before the scanning operation, the user must execute an approach command until detecting a tunneling current. On the left side (Definition), there are scanning controls that determine the work parameters: voltage supplied to the junction, the tunneling current, the scanning range, and the offset. The bottom buttons allow: starting the scan, stopping the scan, stopping and keeping the last scan frame, and erasing a picture. At the centre of the screen a picture is received dynamically during the scan process. In Figure 5, raw data of a graphite picture (3nm by 3nm in size), without image processing, is shown. Additionally, the software has options of image processing, displaying cross sections of the XY plane and displaying a 3-D picture.

6. Costs and Specifications

The central motif in building the system was achieving atomic resolution at a very low cost. The overall cost for the system, produced in a quantity of 10 units, is around $500. A production cost such as this allows for a user cost of less than $5,000. The specifications for the system appear in the following table:

Table 1 The educational STM specifications.

System Parameter	**Value**
Scan Range	1 μm XYZ
Step Size	0.3 ∑
Maximum Sample Size	10 mm
Probe	Platinum-Iridium
Controller Dimension	10 x 15 x 20 cm
Head Dimension	10 x 12 x 10 cm
Computer interface	USB or EPP
GUI Platform	CVI Software
Operation System	Windows, Linux

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