2007 Korea-Japan Joint Workshop on Advanced Semiconductor Processes and Equipments (ASPE 2007), Proceedings, pp. 285-291, Busan, Korea. (October 4-6, 2007).

Development of Compact Scanning Probe Microscope System: STM Unit, AFM/STM Unit, SPM Controller and Control Software

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We developed a compact and carryable scanning probe microscope (SPM) system for observation of surfaces with nano- and micro-meter scales in air. The SPM system consists of a scanning tunneling microscope (STM) unit [diameter: 74 mm, height: 82 mm], a combined atomic force microscope (AFM) and STM unit [width: 100 mm, height: 147 mm, depth: 100 mm], an SPM controller [height: 133 mm, width: 320 mm, depth: 230 mm] and a control software. The STM unit provides atomic resolution image in constant current and constant height modes, and the combined AFM/STM unit has several kinds of measurement AFM modes, that is, DC-mode, AC-mode: amplitude detection (AD), AC-mode: phase detection (PD) and AC-mode: frequency detection (FD). Observations of atoms on graphite surface by the STM unit and structure of aluminum layer of a compact disc by the AFM/STM unit were performed. The SPM system with compact and low-cost may be suitable for use in not only research but also education like student experiments in university and technical college, and lectures of science in high school.

1. Introduction

A scanning probe microscope (SPM) that enables us to observe surfaces in resolution of nanoscale has been used in researches in various fields such as physics, chemistry, material, biology and so on. An important advantage to use the SPM is that one can observe samples in various environments, in air, vacuum and liquid. There are several types of microscopes that differ by probes; representative ones are a scanning tunneling microscope (STM) [1] and an atomic force microscope (AFM) [2]. The STM is used to observe atomic and molecular images on surfaces of conductive samples; it is possible to apply for study on bonding properties of atoms [3] and dynamic diffusion of atoms [4, 5] and so on. In AFM it is easy to observe surface structures of not only conductive materials but also insulating ones. Although nowadays there are many commercial SPMs, in the generality they are large in size and costly.

In this study, we developed a compact and carryable SPM system with functions for observation and data processing. The SPM system consists of an STM unit, a combined AFM/STM unit, an SPM controller and a control software. Because of small size and simple structure, manufacturing cost was reduced in our developed SPM. Therefore, this compact SPM system can be used for not only research and development but also education.

2. Fabrication of the compact SPM

2.1 Basic configurations of STM and AFM

The operation principles [6, 7] of the STM and AFM is to detect physical information by a proximity probe from a sample surface, and to make a map of the information, such as tunneling current, atomic force, light and structure. When a small current that flows in space between a conductive probe tip and a sample by the tunnel effect is detected as shown in Fig. 1 (a), it becomes

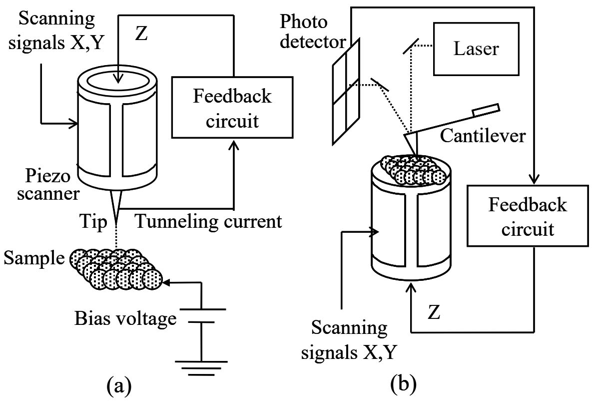

Fig.1 Basic configurations of (a) STM and (b) AFM

the scanning tunnel microscope (STM). If atomic force between an atom of probe on cantilever and an atom of sample surface is detected, it becomes an atomic force microscope (AFM) (Fig. 1 (b)). In fact, since the STM and the AFM have common mechanics and electronics, some SPMs can work for the STM or AFM by changing some parts. In the STM (Fig. 1 (a)) a voltage between the tip and the sample is applied for passing a tunneling current; the tunneling current is kept constant by controlling tip Z height using a feedback control system and a piezo scanner. Then, scanning tip in X and Y directions by the piezo scanner, an atomic image of the sample is obtained by monitoring the feedback signal. In the AFM (Fig. 1 (b)), torsion of the cantilever caused by the atomic force (attraction and repulsion) between the cantilever and the sample is detected by a laser diode and a quad element photodiode. Imaging method of the AFM is same to one of the STM.

2.2 STM measurement in the compact SPM system

The STM unit is used with the SPM controller and the control software of Windows XP. Fig. 2 shows a block diagram for STM measurement by the compact SPM system, which is simpler than one for AFM measurement because the circuits indicated by dashed lines in the block diagram are not used in STM measurement. The control software in a MS-Windows host computer manages the entire SPM system; commands from the host computer is sent to a 32 bit SH-4 microcomputer (SH7750R, 240 MHz) in the SPM controller through an USB 1.1 interface. The SPM controller consists of this SH-4 microcomputer, digital circuits, 16 bit analog-to-digital converters (ADCs), 16 bit digital-to-analog converters (DACs), and analog circuits, interface circuits and power supplies for ±180V, ±15V, +12V, +5V, and so on. Figure of the SPM controller having these electronics is shown in Fig. 3, whose size is enough small, that is, 133 mm in height, 320 mm in width and 230 mm in depth.

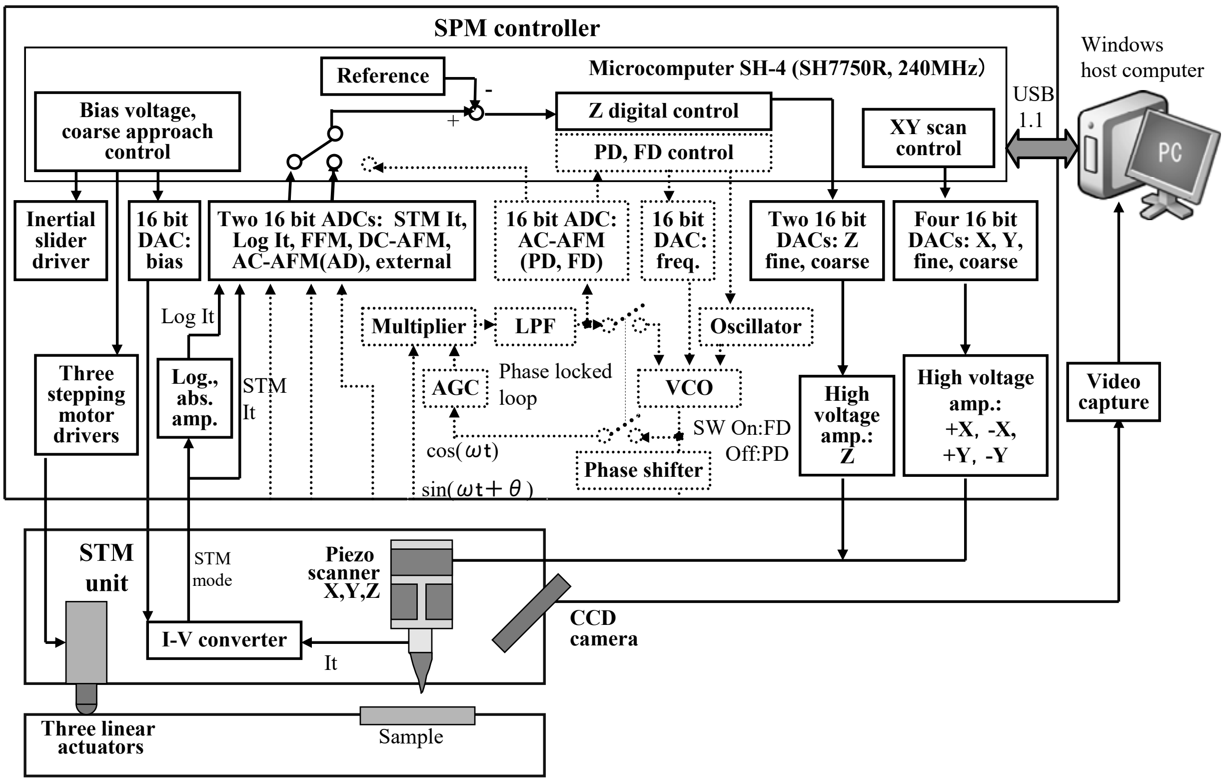

Fig. 2 Block diagram for STM measurement with the STM unit in the compact SPM system

In STM measurement, a bias voltage from the 16 bit DAC (Fig. 2) is applied to the non-inverting input of an ultralow input bias current operational amplifier (AD549JH, Analog Devices), which is a current-to-voltage (I-V) converter with a resistor of 100 MΩ connected between the inverting input and the output. The signal voltage of the tunneling current is obtained by removing the bias voltage from the output voltage of the I-V converter by using a differential amplifier. The voltage that corresponds to the tunneling current is processed through the absolute value circuit and the logarithm circuit to obtain the signal corresponding to distance *d*, since the tunneling current is expressed by $I \propto \exp(-2\kappa d)$. This signal is read by the 16 bit ADC; then, the SH-4 microcomputer calculates a feedback value by digital PI control method using difference between this read value and a reference. As the result, the feedback voltage is produced by two 16 bit DACs for fine and course movements to control the tip height. These two voltages are added as gain of 1 and gain of 16 in the high voltage operational amplifier (PA140CX, Apex); finally, it is applied to Z electrode of a tube piezo scanner. Imaging the feedback signal to the Z piezo scanner is called to be the constant current mode; imaging the tunneling current with slow feedback response is called as the constant height mode in STM measurement. The compact SPM system provides these two measurement modes (Table I).

Fig. 3 Photograph of the SPM controller. Height: 133mm, width: 320mm, depth: 230 mm.

Table I Measurement modes of the compact SPM system

	Measurement modes
STM unit	Constant current
	Constant height
	STS
AFM/STM unit	DC-mode (Contact mode)
	AC- mode, Amplitude detection (AD)
	AC- mode, Phase detection (PD)
	AC- mode, Frequency detection (FD)
	Constant current (in STM)
	Constant height (in STM)
	STS
	DC-FFM (friction force microscope) mode

To form triangular wave signal for scanning in X direction, two signals from 16 bit DACs for fine and course movements is added as gain 1 and gain 16 in high voltage operational amplifier (PA140CX, Apex). Produced +X signal and –X one that is the inverted signal are applied to two +X and –X electrodes of the tube piezo scanner (Fig. 2). Same procedure is employed for the +Y and -Y electrodes of the tube scanner.

For course approach of the tip to the sample, the SPM controller equips two kinds of drivers (Fig. 2), that is, for three linear actuators that consist of stepping motors, fine screws and position sensors, and for one inertial slider. Although the STM unit uses the three linear actuators, the inertial slider can be used for other handmade SPM. Moreover, since a small CCD camera is attached in the STM unit, the image of tip and sample is monitored on the display of the host computer using a video capture board. In the control software, bias voltage, tunneling current, scanning speed, feedback parameters of gain and frequency, position of the tip on the sample, scanning direction, tip approach and so on can be set. These operation menu windows, STM image viewing window, signals viewing window, and CCD camera image window are shown on the display. In addition, this control software has the image processing functions like 2D low pass filter and FFT filter, 3D viewer and etc. Besides, measurement of scanning tunneling spectroscopy (STS) is available (Table I) by direct measurement of the tunneling current, or measurement with a lock-in amplifier.

Fig. 4 (a) shows the developed STM unit, which has compact size with a diameter of 74 mm and height of 82 mm. It is separated to an upper part and an under one. The upper part (Fig. 4 (b)) consists of the three linear actuators, the piezo scanner and the I-V converter, and the under part (Fig. 4 (c)) includes a sample holder pushed up to the upper part by two springs, and fine screws for sample positioning. Distance between the tip in the upper part and the sample in the under one are controlled by the three linear actuators.

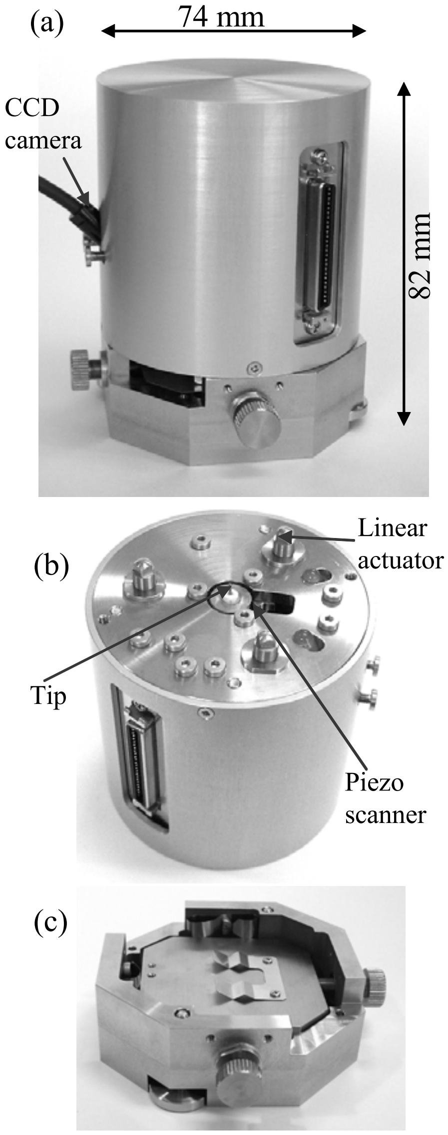

Fig. 4 (a) The STM unit. (b) Bottom view

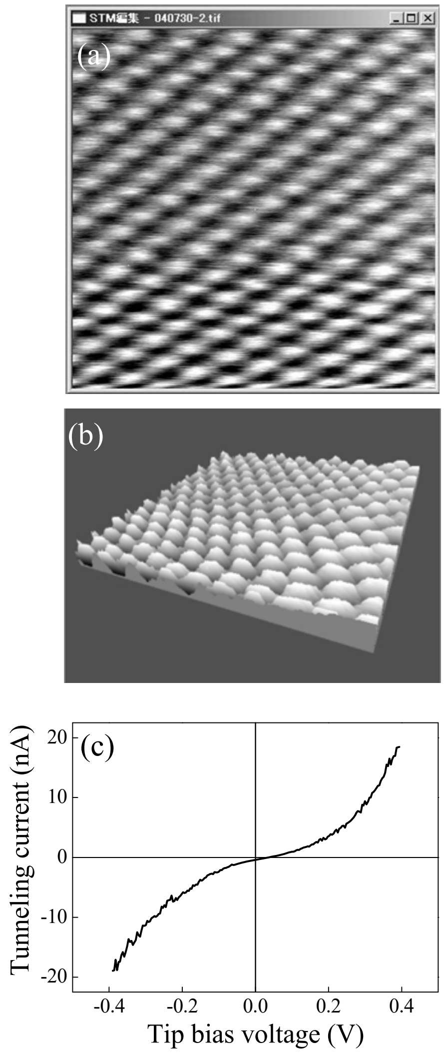

Fig. 5 (a) STM topographic image of a graphite sample. Scanning distance is 2.2 nm. Constant current mode. (b) 3D image of the surface. (c) I-V curves on the sample.

Fig. 5 (a) shows atomic image of the highly orientated pyrolytic graphite (HOPG) surface using the STM unit. In layer structure of the graphite, atomic position of carbon six-membered ring plane is shifted. So, density of states (DOS) of surface atom in the graphite changes whether an atom exists in the under layer; therefore, half of surface atoms of six six-membered ring become bright in STM image because of large DOS and consequent large tunneling current. Fig.5 (b) shows 3D image of the graphite surface. Fig. 5 (c) shows obtained I-V curve on the surface. We can conclude that the SPM system achieved atomic resolution since images of graphite surface atoms were observed clearly as shown in Fig. 5.

2.3 AFM measurement in the compact SPM system

For AFM measurement, the AFM/STM unit is connected to the SPM controller (Fig. 6). The SPM system with the AFM/STM unit has four measurement modes (Table I) for the AFM, that is, DC-mode, AC-mode: amplitude detection (AD), AC-mode: phase detection (PD), AC-mode: frequency detection (FD). As shown in Fig.1 (b) and Fig. 6, reflected laser beam from the cantilever is detected by a quad element Si PIN photodiode (S6695-01, Hamamatsu Photonics) in the AFM/STM unit. In the DC-mode that is called as the contact mode, a value of (a1+a2-b1-b2)/(a1+a2+b1+b2) is obtained from the quad elements photodiode, posterior four I-V converters (OPA404KU, Burr Brown) and analog divider (MPY634, Burr Brown) (a1 to b2 are indicated in Fig. 6). Then, this value is used for the digital PI feedback control with the reference.

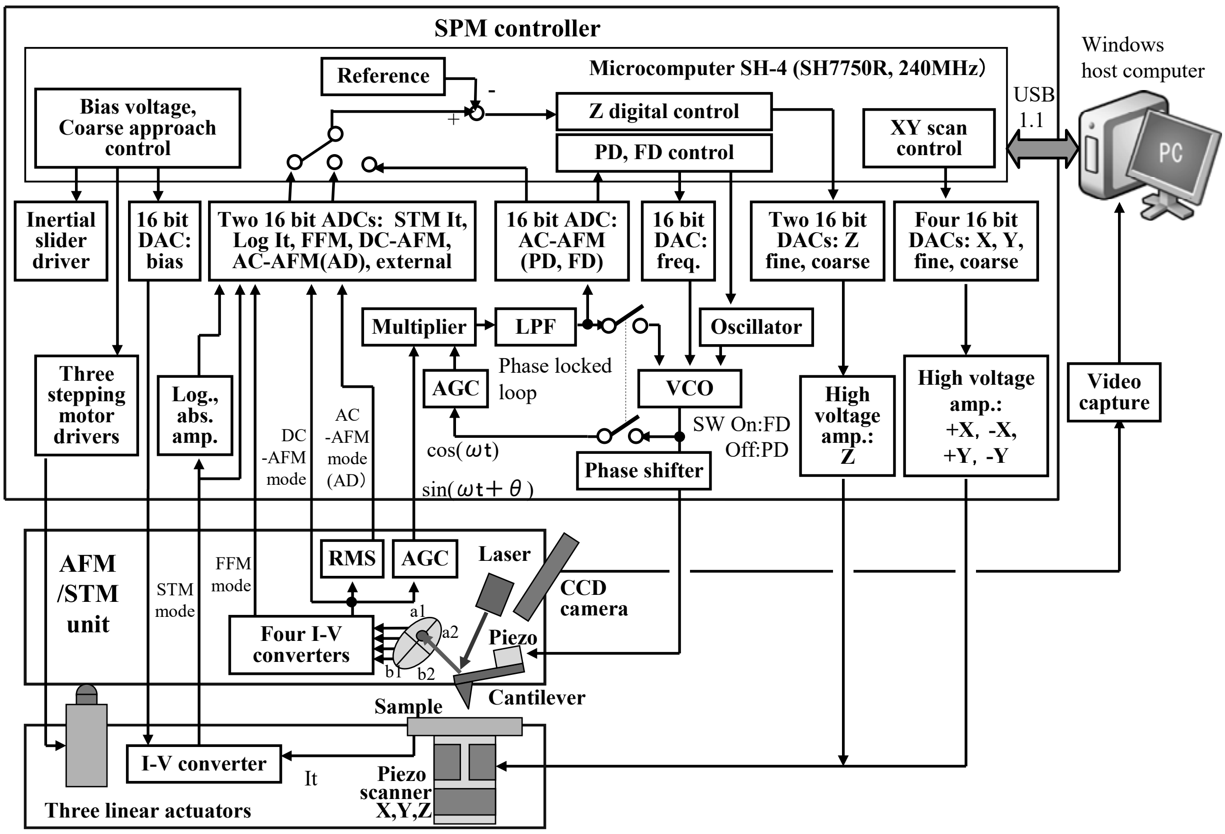

Fig. 6 Block diagram for AFM measurement with the combined AFM/STM unit in the compact SPM system

In the amplitude detection (AM) of AC-mode that is called as the tapping mode, the cantilever is oscillated by a piezo plate attached to the cantilever holder (Fig. 7 (c)). The vibration of cantilever is obtained by a value of root-mean-square (RMS) of [(a1+a2-b1-b2)/(a1+a2+b1+b2)] to use for digital PI feedback control (Fig. 6) to control the distance between the cantilever and sample. In the phase detection (PD) and the frequency detection (FD) of AC-modes, the response signal of cantilever vibration (a1+a2-b1-b2) is processed by an auto gain control (AGC) circuit; a multiplier (MPY634, Burr Brown) generates a phase difference between excitation and response signals. When excitation and response signals are $A\cdot\cos(\omega t)$ and $A\cdot\sin(\omega t+\theta)$ respectively, output from this multiplier becomes $A\cdot\cos(\omega t)\cdot A\cdot\sin(\omega t+\theta)/10$. By a low pass filter (LPF) that is the loop filter of the phase locked loop (PLL) for elimination of frequency doubled components of 2θ, signal of $A^2/20\cdot\sin\theta$ is obtained for feedback control, which is correspond to phase shift. If the switch is off in the PLL circuit (Fig. 6), it becomes the phase detection (PD) mode of AC-mode. If the switch is on in the loop, the PLL circuit works for the frequency detection (FD). Time averaged DC signal $A^2/20\cdot\sin\theta$ is entered to the voltage controlled oscillator (VCO) that produces the excitation signal that is same to the response signal in frequency and phase. The signal of $A^2/20\cdot\sin\theta$, which corresponds to difference frequency Δf, is used for feedback control.

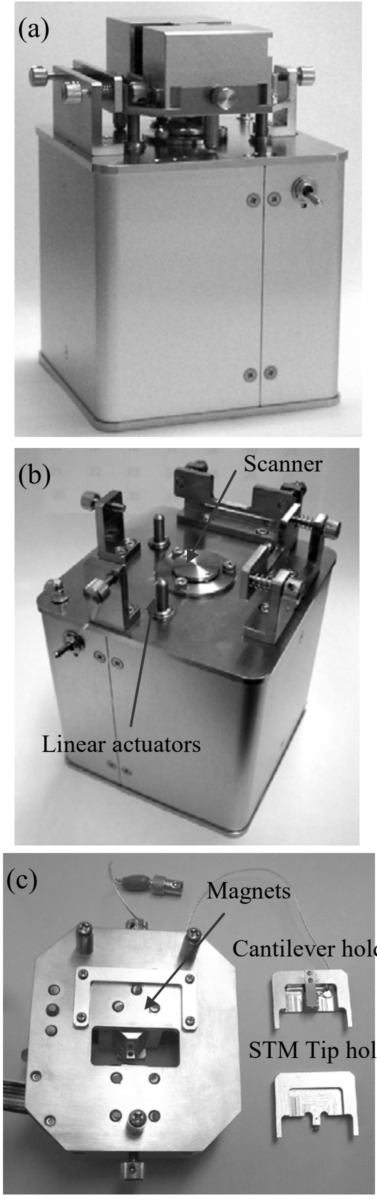

Fig. 7 (a) The combined AFM/STM unit. (b) Top view of under part and (c) bottom view of upper part.

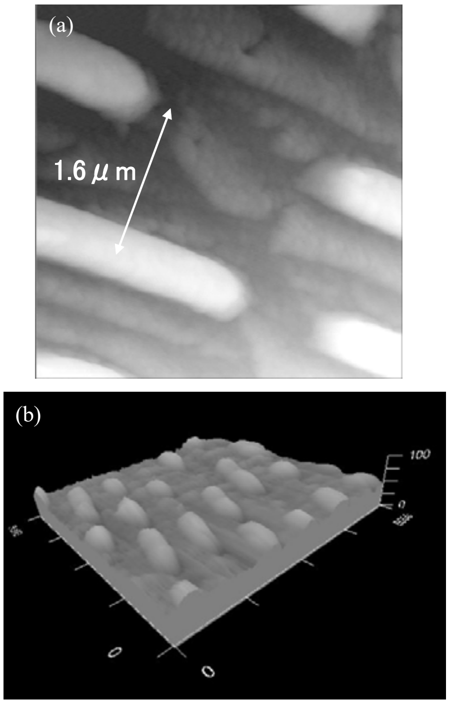

Fig. 8 AFM topographic image of aluminum layer of a compact disc (CD). Amplitude detection (AD) of AC-AFM is used. (b) 3D image of the surface.

The developed combined AFM/STM unit is also compact with size of 100 mm in width, 147 mm in height and 100 mm in depth as shown in Fig. 7 (a). Fig. 7 (b) shows an under part that includes the tube piezo scanner, the three linear actuators and the electronic circuits; Fig. 7 (c) shows an upper part that consists of a laser diode, the quad element photodiode and the four I-V converters (Fig. 6). Because the upper part can attach a cantilever holder or a tip one by magnets, it can be used for not only the AFM measurement but also the STM one. Position of the upper part is adjustable by fine screws in X and Y directions, and also positions of the laser diode and photodiode inside the upper part are adjustable by fine screws.

AFM observation is performed by using the AFM/STM unit. Fig. 8 (a) shows one example of AFM image of aluminum layer of a compact disc (CD) after peeling from a polycarbonate plate, which is obtained by the amplitude detection (AD) method of AC-AFM mode. Long line protrusions that correspond to recorded data with the pitch of 1.6 μm are observed. Fig. 8 (b) shows a 3D image of this aluminum layer.

3. Conclusions

We developed the SPM system that consists of the STM unit, the combined AFM/STM unit, and the SPM controller and the control software. Since size of the SPM system is compact in comparison with other commercial SPMs, it can be carried to various places, for example, class room, laboratory and factory. Although up to now an SPM has been mainly used for research in laboratory, it would be used in many fields; one of the fields is education. Our developed SPM system reduced fabrication cost because of small size and not large number of parts. This kind of instrument with compact and low-cost may be suitable for use in education like student experiments in university and technical college, furthermore, lectures of science in high school and junior high school. If students observe atoms and molecules after learning in lectures, educational effect would be large.

Acknowledgments

The work was supported by Cooperation for Innovative Technology and Advanced Research in Evolutional Area (CITY AREA) program: Toyohashi Area, Ministry of Education, Culture, Sports, Science and Technology. Besides, it was supported in part by the venture business laboratory (VBL) in Toyohashi University of Technology, and by the "Core University Program" of JSPS.

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