'88 KACC 1988. 10. 21~22

# System Dynamics of Scanning Tunneling Microscope Unit

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Abstract: G.Binnig and H.Rohrer introduced the Scanning Tunneling Microscope (STM) in 1982 and developed it into a powerful and not to be missed physical tool. Scanning tunneling Microscopy is a real space surface imaging method with the atomic or subatomic resolution in all three dimensions. The tip is scanned over the surface by two piezo translators mounted parallel ( X-piezo and Y-piezo) to the surface and perpendicular to each other. The voltage applied to the third piezo (Z-piezo) translator mounted perpendicular to the surface to maintain the tunneling current through the gap at a constant level reflects then the topography of the surface. The feed back control loop for the constant gap current is designed using the automatic control technique. In the designing process of the feed back loop, the identification of the gap dynamics is very complex and has difficulty. In this research, using some suitable test signals, the system dynamics of the gap including the Z-piezo are investigated. Especially, in this paper, a system model is proposed for the gap and Z-piezo series system. Indicial response is used to find out the model. The driving voltage of the Z-piezo and the tunneling current are considered as input and output signals respectively.

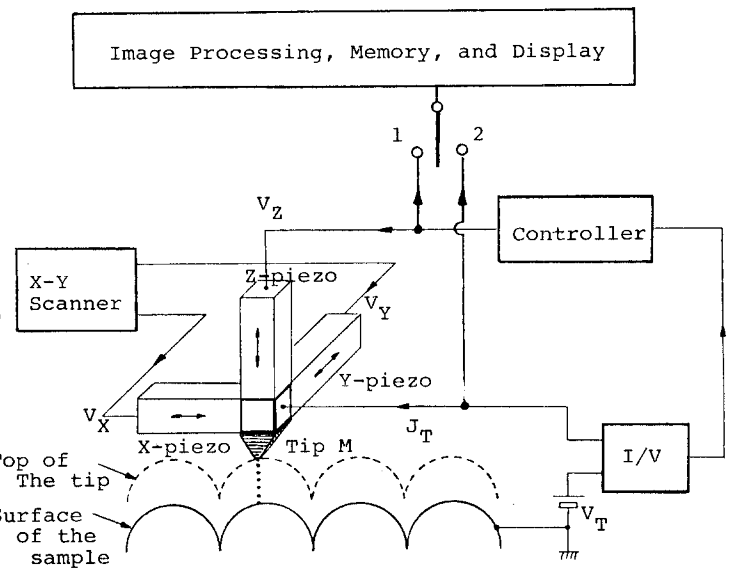



Fig.1 Principle of Scanning Tunneling Microscope

## 1. Introduction

Scanning Tunneling Microscope(STM) is a recently-developed new technique to explore the surface of metal or semiconductor. The STM gives information on the topography with the resolution of atomic scales in the air and the normal temperature. Fig.1 is the principle of the STM. The piezodrives X-piezo and Y-piezo scan the metal tip M over the surface. The controller applies the appropriate voltage $V_Z$ to the piezodrive Z-piezo for constant tun-

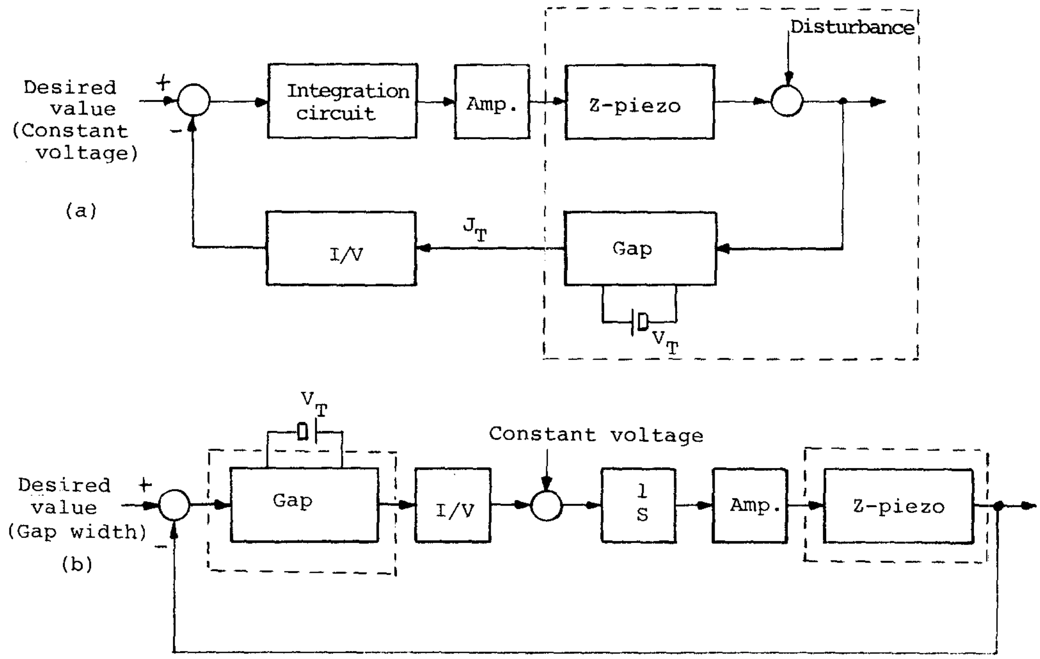



Fig.2 Block diagram of Z-axis feedback control system

nelling current $J_T$ at constant bias voltage $V_T$. On approaching a very sharp tip to the sample surface, the electron clouds of the tip and the sample overlap. Then, for an applied electrical voltage a tunneling current can be detected and monitored ( : for example 50[mV]--- 10[nA]). Since the clouds of electrons decay exponentially away (approximately) from tip and sample, by keeping the tunneling current constant and thus controlling the tip-to-sample distance via an electronic feedback circuit consisting of three mutually perpendicular piezo actuators, a nearly-constant distance between sample and tip can be achieved. The driving signal of the Z-piezo $V_Z$ or the tunneling current $J_T$ can be stored in the computer memory and can be used for the construction of the topography.

Fig.2 shows the block diagram of the Z-piezo feed back system which is drawn from the viewpoint of automatic control technique. Fig.2 (a) and (b) are considered as the constant-value control system and the follow-up control system(servo-system) respectively. In these block diagrams, the elements which are surrounded by broken lines have difficulty to be identify. The resones of this difficulty are as follows,

(1) The Z-piezo actuator has hysteresis non-linearity.

(2) The relation between the tunneling current and the gap distance is not linear.

(3) The system is very stochastic because of the tunneling current is very sensitive to the gap distance.

## 2. System model

The tunneling current density is given by

$$J=\frac{e^2}{\hbar}\frac{1}{4\pi^2 d}\left(\frac{2m_e\phi_0}{\hbar^2}\right)^{1/2}V_T\exp\left[-2\left(\frac{2m_e\phi_0}{\hbar^2}\right)^{1/2}\times d\right] \quad (1)$$

where e is the electron charge
$m_e$ is the free electron mass
$\phi_0$ is the average barrier height
d is the thickness of the barrier
$\hbar$ is $h/2\pi$ = (Plank's constant)/$2\pi$
$V_T$ is the bias voltage

Equation (1) is plotted in Fig.3. This equation gives a important hint of the system identification of the gap, but does not present the practical system dynamics. In this investigation, an indicial response is employed to obtain the transfer function of the gap and Z-piezo series system. Fig.6 is the practical indicial response which is formed from the average of eight signals. In the case of the noise is ignored and assumed that the system is linear, the frequency transfer function is written as follows,

$$G(j\omega) = \frac{U_y(\omega)+jV_y(\omega)}{U_u(\omega)+jV_u(\omega)} \quad (2)$$

where

$$U_y(\omega) = y_c - \omega\int_0^\infty y^*(t)\sin(\omega t)dt \quad (3)$$

$$V_y(\omega) = -\omega\int_0^\infty y^*(t)\cos(\omega t)dt \quad (4)$$

$$U_u(\omega) = u_c - \omega\int_0^\infty u^*(t)\sin(\omega t)dt \quad (5)$$

$$V_u(\omega) = -\omega\int_0^\infty u^*(t)\cos(\omega t)dt \quad (6)$$

then,

$$|G(j\omega)| = \sqrt{(U_y)^2+(V_y)^2/\ (U_u)^2+(V_u)^2} \quad (7)$$

$$G(j\omega) = \tan^{-1}(\frac{V_y}{U_y}) - \tan^{-1}(\frac{V_u}{U_u}) \quad (8)$$

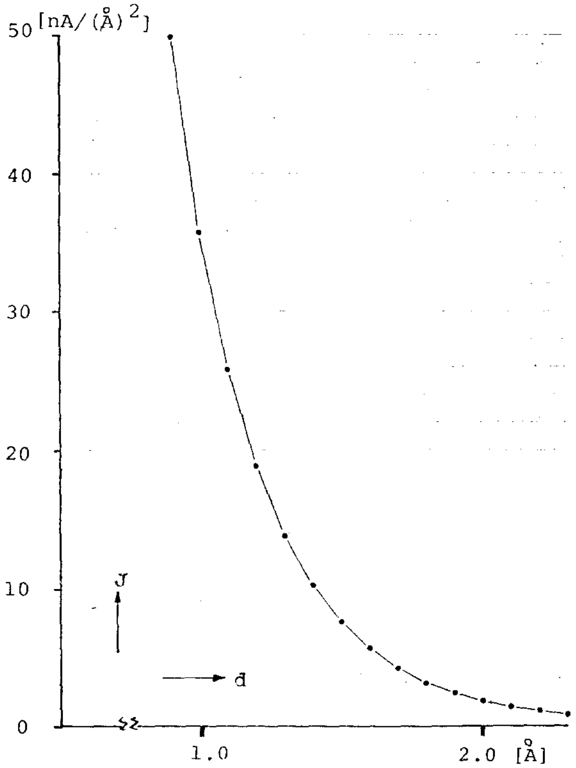
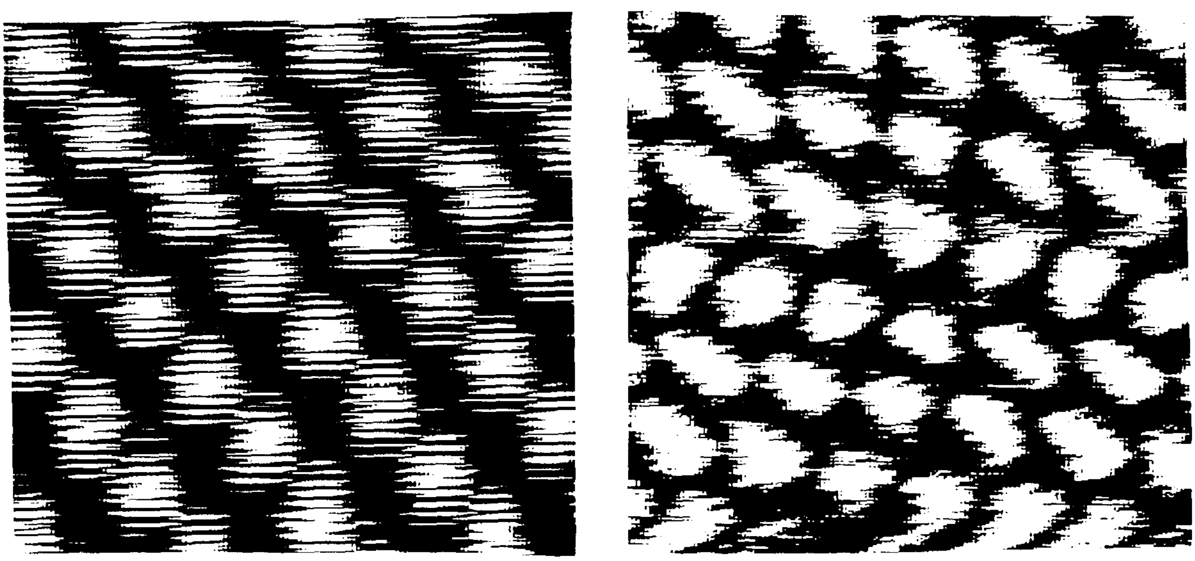



Fig.3 Relationship between tunnel current and thickness of barrier

$$u_c = \lim_{t\to\infty} u(t) \quad (9)$$

$$y_c = \lim_{t\to\infty} y(t) \quad (10)$$



(a)

(b)

Fig.4 Grey scale image of graphite by STM (10[Å]x10[Å])

In case of the noise is considered, the impulse response that expresses the system dynamics is obtained as follows,

$$g(\tau) = \frac{1}{K} E[\hat{\psi}_{uy}(\tau)] \quad (11)$$

where

$$K = \int_{-\lambda}^{\lambda} d(\mu)d\mu$$

$$= \int_{-\lambda}^{\lambda} \hat{\psi}_{uu}(\mu)d\mu \quad (12)$$

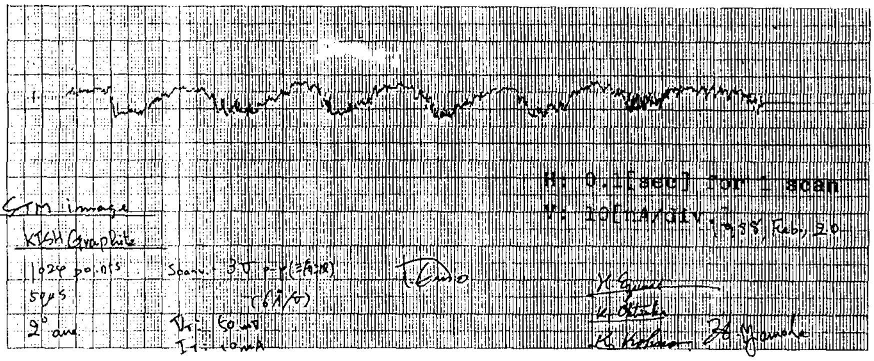



Fig.5 Topographic tunneling current signal with atomic resolution

$$\hat{\psi}_{uu}(\tau,\tau_1) = \hat{\psi}_{uu}(\tau-\tau_1)$$

$$= \begin{cases} d(\tau-\tau_1) & |\tau-\tau_1| \leq \lambda \\ 0 & |\tau-\tau_1| > \lambda \end{cases} \quad (13)$$

$$\hat{\psi}_{uu}(\tau,\tau_1) = \frac{1}{T}\int_0^T u(t-\tau)u(t-\tau_1)dt \quad (14)$$

$$\hat{\psi}_{un}(\tau) = \frac{1}{T}\int_0^T u(t-\tau)n(t)dt \quad (15)$$

$$\hat{\psi}_{uy}(\tau) = \int_{-\infty}^{\infty} g(\tau_1)\hat{\psi}_{uu}(\tau,\tau_1)d\tau_1 + \hat{\psi}_{un}(\tau) \quad (16)$$

E[·] : Expected value

u(t) : White noise

n(t) and u(t) are independent

$$\lim_{T\to\infty}\frac{1}{T}\int_0^T n(t)dt = 0 \quad (17)$$

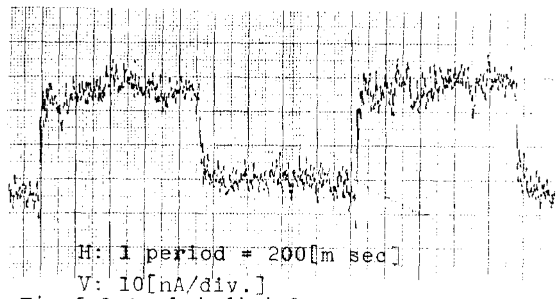



Fig.6 Actual indicial response of gap and Z-piezo series system

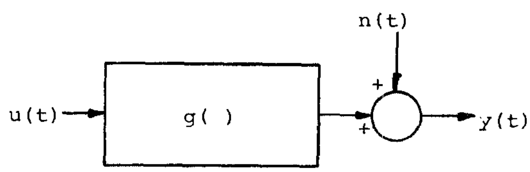



Fig.7 The gap and Z-piezo series system disturbed by additive noise

Fig.5 shows the detected tunneling curent scanning the tip on the surface of graphite. Fig.4 (a),(b) are the Gray scale image of graphite by STM.

## 3. Conclusions

In this paper, the system model of gap and Z-piezo was discussed. The inditial response has non-linearity and remarkable noise. The model style has to be selected for each purpose. The computation of parameter will be shown in the lecture. The curve fitting test will also be shown.

## References


[1] Othmar Josef Marty : Scanning tunneling Microscope at Low Temperatures, A dissertation submitted to the SWISS FEDERAL INSTITUTE OF TECHNOLOGY ZURICH,(1986)

[2] Paul K. Hansma and Jerry Tersof : Scanning Tunneling Microscopy,J. Appl. Phys. 61(2),15 January,(1987)

[3] Nobuo Mikoshiba,Seizo Morita and Yuri Ishigame : Multilayer Piezoelectric Actuators for Scanning Tunneling Microscope, Proceedings of 7th Symposium on Ultrasonic Electronics Kyoto(1986)