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## THE ATOM-PROBE WITH A FIELD EMISSION ELECTRON SPECTROMETER

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**Abstract** - The basic imaging process of FIM and STM is electron tunneling. Therefore, the clarification of tunneling properties of individual surface atoms is an essential requirement for the deduction of a true topography from a depicted image. Accordingly, a field emission electron energy analyzer was mounted behind the imaging screen of an atom-probe in order to clarify the tunneling property of a surface atom. The advantage of this arrangement is the ability to mass analyze apex atoms and examine the effect of adsorbed contaminants on the tunneling property. The preliminary examination indicates that the sensitivity and energy resolution of the analyzer are high enough for the study of adsorbed hydrogen on silicon.

1 - INTRODUCTION

Since the introduction of the scanning tunneling microscope (STM) /1,2/, it has been realized that the quality of STM images and the electronic state of individual surface atoms surveyed by scanning tunneling spectroscopy (STS) /3-6/ vary significantly with the arrangement and chemical composition of apex atoms /7,8/. Thus, the combined instruments of the STM and FIM were developed to examine the atomic arrangement at the apex of a scanning tip /9,10/. However, the clarification of chemical and electronic states of the apex requires other techniques. A promising technique to clarify the chemical composition of the tip apex is to combine the STM with an atom-probe (A-P) /11,12/ and to mass analyze the apex area. Other technique is to energy-analyze the electrons field-emitted from the tip apex and to probe the electronic state of the apex. Consequently, we mounted an electron energy analyzer in the A-P and attempted to clarify the electronic and chemical states of the apex area.

2 - ENERGY ANALYZER

The high mass resolution A-P /12/ was employed. The A-P has a screen to project field ion images of the tip apex and the screen has a probe hole at its center to let the field evaporated apex atoms fly into the mass analyzer. The energy analyzer for the field-emitted electrons was mounted behind the probe hole of the screen as shown in Fig. 1. The analyzer is mounted on the end of the transfer rod of a vacuum linear motion feedthrough and can be removed from the probe hole area.

The basic configuration of the energy analyzer, Fig. 2, was adopted from the retarding field model /13/. In order to improve the energy resolution, the electrostatic lens focuses the electron beam and gives the electrons normal incidence upon the collector surface. A negative potential as high as the tip potential is applied to the collector and the potential difference between the

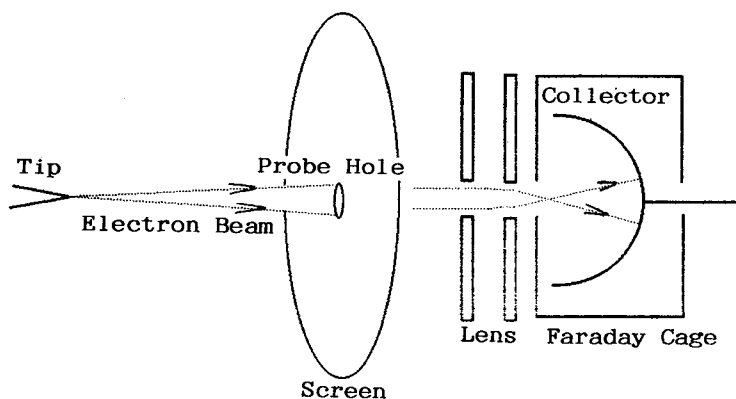


Fig. 1 - Basic configuration of the energy analyzer mounted in the A-P.

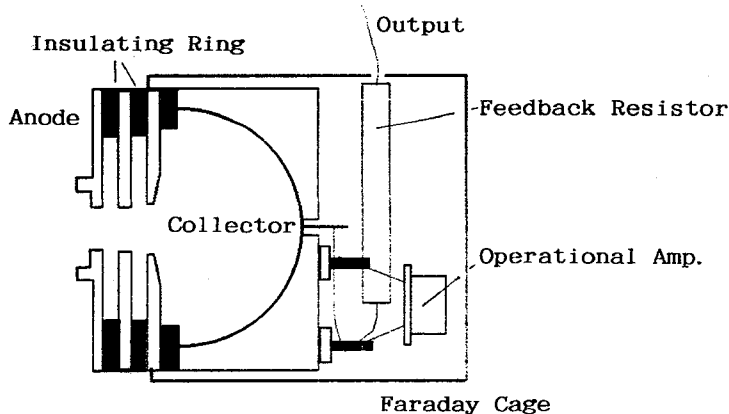


Fig. 2 - Schematics of the energy analyzer.

tip and the collector is the energy of the incident electrons. The collector surface is gold coated in order to avoid the effect of the contaminated layer. The output terminal of the collector is connected with the operational amplifier (Burr-Brown OPA128LM) attached to the Faraday cage of the analyzer. Since the feedback resistor is as high as  $10^9 \Omega$ , the input current of 1 pA generates the output voltage of 1 mV. The voltage signal is transmitted to the differential amplifier outside of the A-P vacuum chamber, Fig. 3. The output signal of the differential amplifier is fed into the isolation amplifier (Burr-Brown 3656BG) to isolate the high voltage applied to the collector.

Tip and collector voltages are controlled by a computer and modulated by a sine wave generated by a function generator. The modulated current signal is detected by a lock-in amplifier and the noise level is significantly lowered. The energy spectrum of field-emitted electrons is obtained by measuring the output signal from the lock-in amplifier as a function of the voltage difference between the tip and the collector.

### 3 - ENERGY RESOLUTION

Tungsten emitters were employed as a reference specimen. The current passed through the probe hole was about 30 pA. The measuring time for each voltage difference was 1.6 sec. Thus, the measuring time of an energy spectrum was a few minutes depending on the number of measuring points. Tip temperature was 50K and the vacuum of the A-P chamber was  $5 \times 10^{-10}$  Torr.

Figures 4(a) and (b) are the energy spectrum of electrons emitted from the W (111) plane and  $R(E)$ , the ratio of the measured current  $j(E)$  to the current

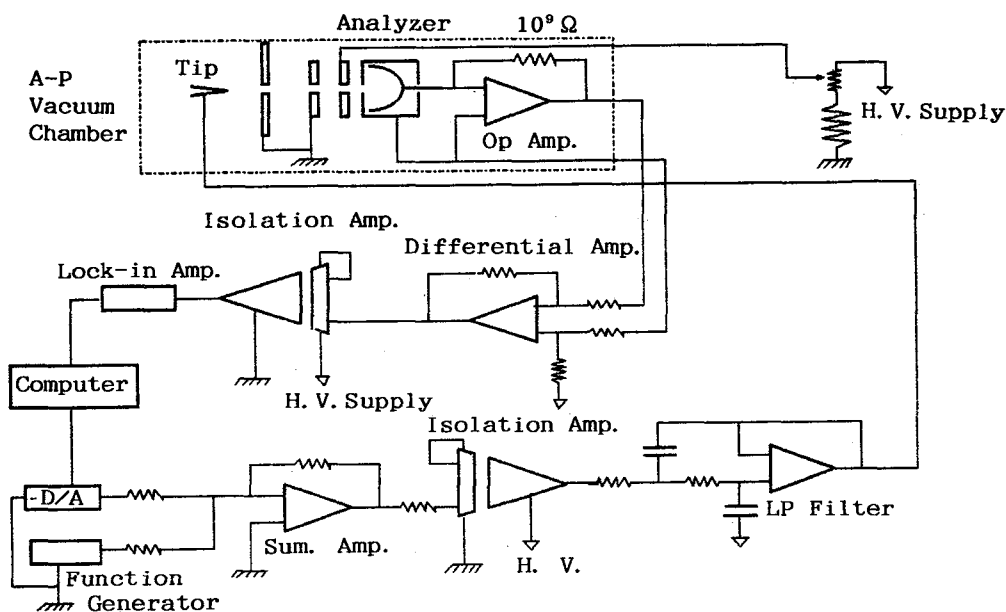


Fig. 3 - Block diagram of the field-emission electron energy analyzer.

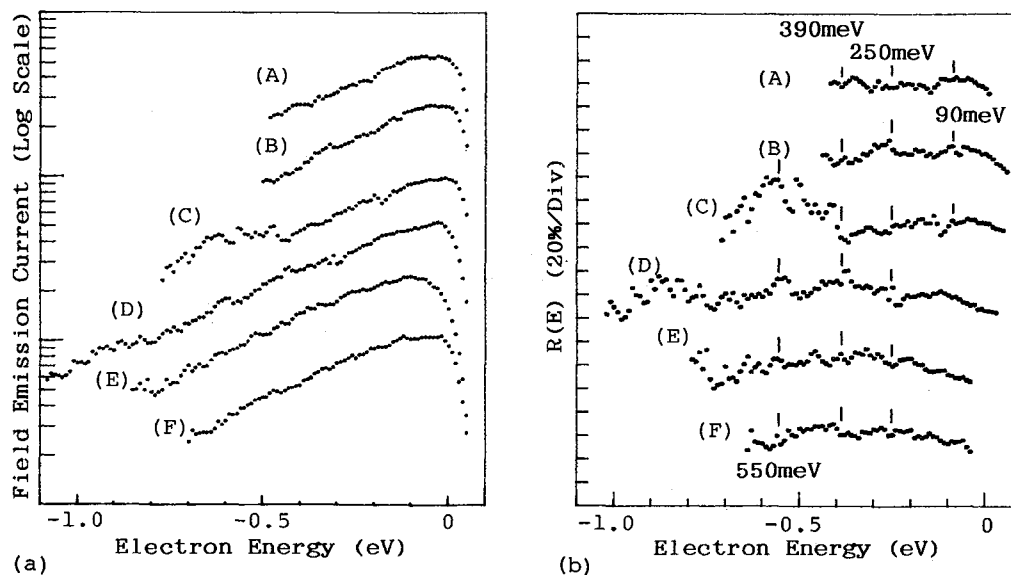


Fig. 4 - (a) Energy spectra of the electrons field emitted from the (111)-oriented W tip. (b)  $R(E)$ , the ratio of the measured current  $j(E)$  to the current theoretically expected from the free electron model  $j_0(E)$ .

theoretically expected from the free electron model, respectively,. The measurement of each spectrum takes 2 min and the spectra (A)-(F) showed the variation of the spectra with time. The sharp current increase at the Fermi level, the high energy side, indicates that the energy resolution of this analyzer is approximately 70 meV. Peaks and discontinuous steps marked at 90 meV, 250 meV, 390 meV and 550 meV in Fig. 4(b) are the effect of adsorption and 550 meV peak is known to be the peak formed by the electrons inelastically scattered by adsorbed hydrogen/14/. The step at 250 meV was also observed for hydrogen adsorbed surface/14/. An interesting finding is the appearance and disappearance of 550 meV peak. It abruptly appeared in R(E) plot (C) of Fig. 4(b) and was

hardly seen in plot (E). This implies that the change of adsorption state and the increase in hydrogen coverage reduce the inelastic scattering of tunneling electrons.

#### 4 - HYDROGEN ADSORPTION ON n-TYPE SILICON

The (100)- and (111)-oriented Si tips were fabricated from a Si wafer with the resistivity of  $0.01\Omega\text{ cm}$ . The energy spectrum of the (100)-oriented tip exhibited a single peak as shown in Fig. 5 and the variation of the spectrum by hydrogen adsorption is not significant. Since the high energy side edge of the peak is 800 meV below the Fermi level, the peak is formed by the electrons emitted from the valence band.

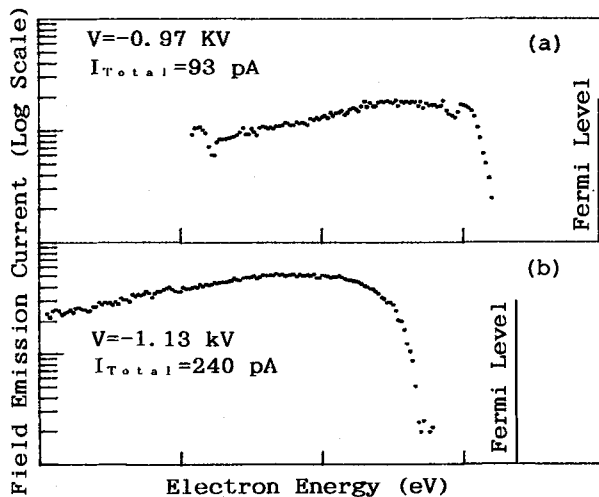


Fig. 5 - Energy spectrum of field emitted electrons from the (100)-oriented Si tip. (a) Tip voltage  $V = -0.97\text{ kV}$ , total current  $I = 93\text{ pA}$ . (b)  $V = -1.13\text{ kV}$ ,  $I = 240\text{ pA}$ .

The spectrum of the (111)-oriented tip has two peaks. The peak at high energy side  $P_H$  is very sensitive to hydrogen adsorption and gradually disappears with hydrogen coverage and the third peak appears at the low energy side, Fig. 6.

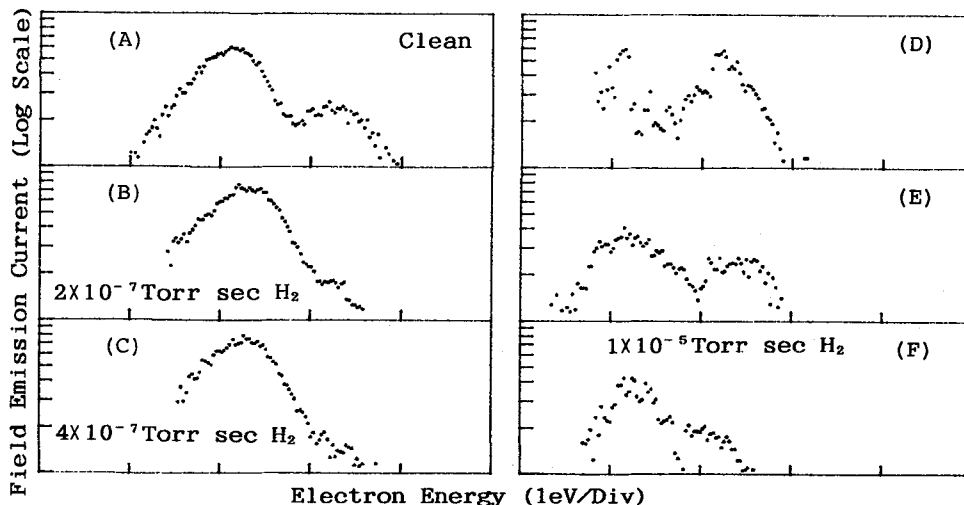


Fig. 6 - Variation of energy spectra of the electrons field-emitted from the (111)-oriented Si tip by hydrogen coverage. Tip temperature:  $50\text{ K}$ . Hydrogen pressure:  $5 \times 10^{-10}\text{ Torr}$ .

Disappearance of  $P_H$  could be the result of hydrogen adsorption forming Si-H bonds and eliminating the unpaired dangling bonds yielding the surface states. The low energy peak  $P_L$  is about 500 meV below  $P_H$ . Thus,  $P_L$  is the peak formed by the electrons emitted from the valence band.

The electron current emitted from a contaminated tip surface was unstable and the reproducibility of a reliable spectrum was poor. Figure 7 shows a mass spectrum obtained by mass analyzing the (100)-oriented Si tip. Detection of  $C^+$ ,  $C^{2+}$  and  $O^+$  suggests that adsorbed carbon and oxygen unstabilize the Si-H bonds.

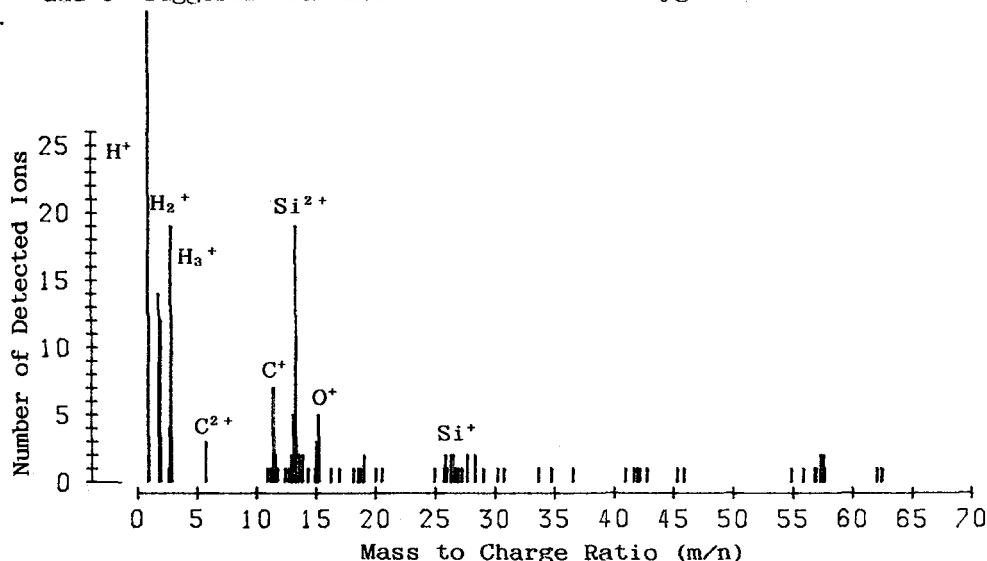


Fig. 7 - Mass spectrum obtained by the A-P analysis of a contaminated (100)-oriented Si tip. Tip temperature: 50K.

The energy spectra of the electrons field-emitted from Si surfaces is about 2 eV below the Fermi level obtained by the W spectrum and shifts to lower energy as the tip voltage increases. The observed linear relation between the lowered collector voltage and the emission current indicates that the shift of the energy spectra is caused by the ohmic effect of the current flowing in the Si tip. The reduced resistance of the tip by the spectrum shift is  $2 \times 10^9 \Omega$ . Then, the shifted Fermi level for Si is about 1.5 V lower than the Fermi level of W as shown in Fig. 8.

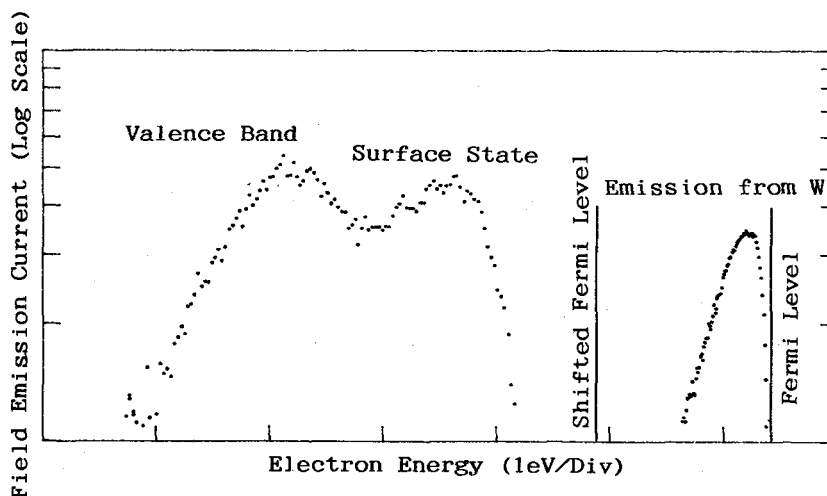


Fig. 8 - Relation of Fermi levels for Si and W, surface state and valence band.

5 - CONCLUSION

Present study clearly indicates that the installation of an electron energy analyzer is a promising approach to clarify the electronic state and chemical composition of a tip apex. The present results also suggest that the refinement of the analyzer and the combination of the analyzer installed A-P with an STM would basically improve the reproducibility and reliability of the STM/STS study.

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