Development of atomic force microscopy combined with scanning electron microscopy for investigating electronic devices

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ABSTRACT
Atomic force microscopy (AFM) was combined with scanning electron microscopy (SEM) to investigate electronic devices. In general, under observation using an optical microscope, it is difficult to position the cantilever at an arbitrary scan area of an electronic device with a microstructure. Thus, a method for positioning the cantilever is necessary to observe electronic devices. In this study, we developed an AFM/SEM system to evaluate an electronic device. The optical beam deflection (OBD) unit of the system was designed for a distance between the SEM objective lens and a sample surface to be 2 cm. A sample space large enough to place an actual device was created, using a scan unit fabricated with three tube scanners. The scanning ranges of the scan unit are 21.9 μm × 23.1 μm in the XY plane and of 2.5 μm for the Z axis. The noise density in the OBD unit was measured to be 0.29 pm/Hz0.5, which is comparable to noise density values reported for commercial AFM systems. Using the electron beam of SEM, the electron beam induced current (EBIC) is generated from a p–n junction of a semiconductor. Using the EBIC, the cantilever was positioned at the p–n-junction of a Si fast recovery diode (FRD). In addition, scanning capacitance force microscopy (SCFM) and Kelvin probe force microscopy (KFM) were combined with the AFM/SEM system. The SCFM and KFM signals were in qualitative agreement with the expected carrier density distribution of the p and n-regions of the Si-FRD.

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I. INTRODUCTION

One of the commonly used scanning probe microscopies (SPMs) is atomic force microscopy (AFM), which can map the surface topography of a sample with high spatial resolution. Some types of AFMs can also map physical properties such as magnetism, elasticity, and electric charge. There have been many reports evaluating electronic devices using SPM techniques, such as observing the stress distribution of a bar structure and evaluating the potential distribution of an electronic device. These reports suggest that AFM is a suitable tool for evaluating a device because it works in various environments such as air, vacuum, and liquid media.

In many reports, specially prepared devices for observation have been used as samples for AFM. In our previous reports, as a more appropriate method for evaluating devices, actual commercial devices under applied bias voltages were examined using AFM. The depletion region of a Schottky barrier diode was evaluated using scanning capacitance force microscopy (SCFM). A fast recovery diode (FRD) under conductivity modulation was observed using Kelvin probe force microscopy (KFM). SCFM and KFM combined with AFM are useful methods of evaluating...
electrical properties. An SCFM image depends on the carrier density and polarity of a semiconductor. A KFM image depends on the contact potential differential between the cantilever and the sample.

One of the problems in the observation of an electronic device using AFM is the method used for positioning the cantilever at a polished device surface. In general, a cantilever is positioned based on observations made with an optical microscope whose spatial resolution is not sufficient to observe a device with a microstructure. Moreover, it is impossible to find the carrier density distribution of a device using an optical microscope. Here, AFM is combined with scanning electron microscopy (AFM/SEM) to solve these problems because the spatial resolution of SEM is much higher than that of optical microscopy. In addition, an electron beam induced current (EBIC) is generated by irradiating a p–n junction of a semiconductor device with the electron beam of SEM. EBIC imaging combined with SEM has been used to analyze the generation and recombination of electron–hole pairs in a solar cell. Thus, measurements using an EBIC might be a suitable method to position a cantilever at the p–n junction of a device.

In previous reports, several AFM/SEM systems have been developed. The sample space of the commercial AFM/SEM of SEMILAB is too small for an actual device. One of the AFM/SEM systems can observe a sample at an oblique angle to the sample surface, and another needs a self-sensitive cantilever. Here, a conductive self-sensitive cantilever might be a suitable tool for an AFM/SEM system in the small vacuum chamber of an SEM system. However, there are a few conductive self-sensitive cantilevers. Thus, an AFM/SEM system capable of utilizing various types of conductive cantilevers would become a powerful tool for evaluating electronic devices.

In this study, we developed an AFM/SEM system for evaluating electronic devices. From secondary electron (SE) and EBIC signals, a cantilever could be positioned at a p–n junction on the polished surface of a commercial Si-FRD. The p–n junction was observed using the AFM, KFM, and SCFM functions of the AFM/SEM system.

II. EXPERIMENTAL PROCEDURE
A. The AFM/SEM system used for evaluating electronic devices

The vacuum chamber of the SEM system (HITACHI S-3700N) used in this study consists of a cylindrical space whose diameter and height are 20 and 11 cm, respectively. The experimental setup of the AFM/SEM system in this space is shown in Fig. 1(a). To utilize various cantilevers, an optical beam deflection (OBD) method was used to detect cantilever deflection. Many commercial AFM systems use the OBD method because optical beam alignment for the OBD method is easier than that required for an interferometer. In general, a laser beam passes through a beam splitter before reaching the cantilever, which is set at an oblique angle to the sample. In this case, the reflected beam from the cantilever is selectively detected using a photodetector. However, the beam splitter could not be used here due to the SEM objective lens, as shown in Fig. 1(a). In addition, the spatial resolution of SEM decreases as the distance between the SEM objective lens and the sample is increased. Thus, the geometry of the OBD unit was designed for the distance to be 2 cm.

As shown in Fig. 1(a), the AFM unit was designed to be 10 cm height to allow it to be placed inside the vacuum chamber. A laser beam generated from a laser module (LD: Takenaka Optonic LDV167S) is focused using a lens (Sigmakoki SLB-10B40PIR1) and then is reflected using a mirror to irradiate the cantilever. The LD and lens are mounted on a positioner which consists of an XY stage (Sigmakoki TADC-252WS) and piezomotors (Newport 8353). The reflected beam from the cantilever is detected using a quadrant photodiode (QPD: Hamamatsu Photonics S4349). The QPD is mounted on a positioner which consists of an XY stage (Sigmakoki TADC-252WSR) and a piezomotor (Newport 8353). For optical beam alignment of the LD and the QPD, these positioners are controlled using control signals from outside of the chamber. Current signals from the QPD are converted to voltage signals using current-to-voltage
A p–n junction with rectifying characteristics can be used in various electronic devices, such as diodes, transistors, and thyristors. Electron–hole pairs can be generated by irradiating a semiconductor with the electron beam of SEM. When the irradiated area includes a p–n junction, electrons and holes are moved by the built-in electric field of the p–n junction. These charges are transferred outside of the semiconductor and can then be detected as current using an ammeter. This current is defined as an EBIC, which is generally converted to a voltage signal using an IV converter. An EBIC signal can be recorded using the SEM system and synchronized with the scanning of the electron beam to obtain an EBIC image. Thus, SE and EBIC images can be obtained simultaneously using the SEM system.

An EBIC signal detector was developed with an IV converter, an analog switch, and a programmable filter. The analog switch (Maxim Integrated DG419CJ+) is inserted before the IV converter to prevent applying a modulation signal from the KFM or SCFM to the converter. The IV converter and the voltage follower consist of a twin operational amplifier (Texas Instruments OPA2107). The operational amplifier was selected to reduce the input capacitance of the IV converter. Here, the sizes of the feedback resistor, \( R_f \), and capacitor, \( C_f \), are 4.7 MΩ and 5 pF, respectively. The bandwidth of the IV converter, \( f_{ IV } \), is assumed as a second corner frequency which is given by

\[
f_{ IV } = \frac{1}{2 \pi R_f C_t}.
\]

Using Eq. (3), the bandwidth of our IV converter was calculated to be 6.77 kHz. The analog switch, the IV converter, and the voltage follower were placed near the device holder to reduce input capacitance. On the outside of the chamber, a commercial programmable filter (NF 3628) was used as a band elimination filter (BEF) to eliminate the noise derived from a commercial power supply with a frequency of 60 Hz.

A commercial Si-FRD (ROHM RFU10TF6S) was used as a sample with a p–n junction. In our previous report, the Si-FRD was cut and then polished by mechanical polishing to probe the semiconductor region by SPM. In this study, the device was polished by not only mechanical polishing but also chemical mechanical polishing (CMP) to reduce any polishing traces. A colloidal silica slurry (FUJIMI INCORPORATED COMPOL80) was used for the CMP process. In the CMP process, the weight, the rotation speed of the plate (FUJIMI INCORPORATED SURFIN XXX-5), and the polishing time were 0.5 kg, 30 rpm, and 15 min, respectively.

Figure 2 shows the experimental setup used to measure the EBIC signal to investigate the polished Si-FRD. Also in this figure, an EBIC signal diagram is indicated with a red dashed line. To obtain the EBIC signal, the cathode (K) electrode of the polished device was only connected to the IV converter through the analog switch. On the other hand, the anode (A) electrode of the polished device was connected to a grounded electrode.

### C. KFM and SCFM for evaluating the polished device

Figure 2 shows a schematic diagram of the AFM, KFM, and SCFM techniques used to investigate the polished Si-FRD. In
A signal based on this fundamental component is detected as a deflection signal from the cantilever using a lock-in amplifier (LIA). In KFM, $V_{bias}$ is recorded as a surface potential by canceling $\phi_{CPD}$ using a bias feedback circuit. Here, FM-KFM has been reported to improve the spatial resolution of KFM in a vacuum environment. In this study, when using FM-KFM, a resonance frequency shift derived from the electrostatic force was demodulated using the PLL and a LIA (Anfatec 408/2). Here, $V_{bias}$ was regulated using a homemade bias feedback circuit with a PI controller. The amplitude and frequency of the modulation signal for KFM were set to be 2.84 V and 800 Hz, respectively. In addition, a low-pass filter (LPF) with a cutoff frequency of 150 kHz (NF 3628), the cantilever was stably excited in the first resonance mode.

An SCFM image is obtained using the third harmonic component of the electrostatic force between the cantilever and the sample. If the sample is a semiconductor, the capacitance, $\delta$, consisting of the cantilever and the semiconductor, depends on the bias voltage. In this case, the third harmonic component of the electrostatic force is given by

$$F_{3ac} = \frac{1}{8} \frac{\partial^2 C(Z, V_{bias})}{\partial Z \partial V} V_{ac}^3 \cos(3\omega t). \quad (6)$$

Here, the absolute value and phase of the differential capacitance, $\frac{\partial^2 C(Z, V_{bias})}{\partial Z \partial V}$, depend on the carrier density and polarity (n or p) of the semiconductor. A signal based on the third harmonic component is detected as a deflection signal from the cantilever using a LIA, and then, this signal is recorded to obtain an SCFM image. To improve the force sensitivity of SCFM, the third harmonic angular frequency is adjusted to the first resonance angular frequency of the cantilever with a high quality factor. Here, the amplitude, frequency, and external bias voltage of the modulation signal for SCFM were set to be 2.84 V, 28961 Hz, and 0 V, respectively. In this case, the cantilever was excited at its second resonance frequency to obtain an AFM image. Using a high-pass filter (HPF) with a cutoff frequency of 400 kHz (NF 3628), the cantilever was stably excited in its second resonance mode.

In FM-AFM in the first resonance mode, the phase of the cantilever is orthogonal to the phase of the excitation signal. Here, we assumed that the time response of the third harmonic component was delayed by 90°. Thus, a sine wave component with a phase delay of 90° with respect to the cosine wave component of the third harmonic component was used as the SCFM signal.

To obtain KFM and SCFM images, the analog switch was set to the off state. A driving voltage of $V_{AK}$ was applied to the A electrode of the polished device with respect to the K electrode using a floating power supply. The modulation signal for KFM and SCFM was applied to the K electrode using the bias feedback circuit and a function generator. In addition, FM and SCFM were performed separately because the signal to noise ratio of FM-KFM using the first resonance mode is higher than that using the second resonance mode.

Using the experimental setup as shown in Fig. 2, SE and EBIC signals were used to position the cantilever at the p–n junction of a polished device. After positioning the cantilever, the p–n junction was probed using AFM, KFM, and SCFM.

**Fig. 2.** Experimental setup for measuring an EBIC signal and a schematic diagram of AFM, KFM, and SCFM operation. One of the tube scanners is omitted. An electronic device is evaluated under an applied bias voltage. The red dashed line, black dashed line, and black solid line indicate diagrams of EBIC, AFM, and KFM or SCFM, respectively.

A KFM image is obtained using electrostatic forces based on the contact potential difference, $\phi_{CPD}$, between the cantilever and the sample. A modulation signal applied to a capacitance, $C$, consisting of the cantilever and the sample is denoted by

$$V = \phi_{CPD} - V_{bias} + V_{ac} \cos(\omega t). \quad (4)$$

Here, $V_{bias}$ and $V_{ac} \cos(\omega t)$ are a direct current (DC) component from an external voltage source and an alternating current component, respectively. In this case, a fundamental component of the electrostatic force between the cantilever and the sample is given by

$$F_{ac} = \frac{dC(Z)}{dZ} (\phi_{CPD} - V_{bias}) V_{ac} \cos(\omega t). \quad (5)$$

A KFM image was probed using AFM, KFM, and SCFM.
III. RESULTS AND DISCUSSION

A. Measurement of the thermal Brownian motion of a cantilever

The noise density of the developed OBD unit was determined using the thermal Brownian motion of the cantilever. The same type of cantilever as that used to probe the polished Si-FRD was placed in the cantilever holder of the AFM unit in the vacuum chamber. The input terminal used to provide the excitation signal was grounded, and then, the thermal Brownian motion of the cantilever was measured using a fast Fourier transform (FFT) analyzer (ONOSOKKI, Japan). Figure 3 shows the frequency spectrum of the thermal Brownian motion of the cantilever. The black circles, red solid line, and red dashed line indicate the measured value, fitted curve, and noise density in the detection unit, respectively. The fitted curve was obtained using Eq. (2) and the measured thermal Brownian motion. In Eq. (2), \( k \), \( k_b \), and \( T \) were 2.0 N/m, 1.34 \( \times 10^{-23} \) J/K, and 300 K, respectively. From the fitted curve, the resonance frequency, quality factor, and the noise density in the detection unit were estimated to be 88,550 Hz, 1899, and 0.29 pm/Hz\(^{0.5}\), respectively. The determined quality factor in vacuum might be a valid measurement to commercial AFM systems.

B. Positioning the cantilever at a p–n junction of the polished Si-FRD

The cantilever was positioned at the p–n junction of the polished Si-FRD using the EBIC signal. Figure 4(a) shows the typical structure of a Si-FRD which has a p–n junction. Figures 4(b)–4(e) show SEM images of the polished Si-FRD taken with an acceleration voltage of 15 kV. The strip-shaped structure in the SEM images is the cantilever, where the SE and EBIC signals are indicated with gray and yellow, respectively. The contrasts of Figs. 4(c) and 4(e) were adjusted to put emphasis on the EBIC signals. Figures 4(b) and 4(c) show the SE image and the image of the summed signals of SE and EBIC, respectively. In Fig. 4(b), the semiconductor (Si) and K electrode can be identified from the signal contrasts. In Fig. 4(c), the region of the high EBIC signal corresponds to the semiconductor region, which means that this region includes the p–n junction of the polished Si-FRD. Thus, the cantilever was successfully positioned in this region using the XYZ stage of the AFM/SEM system.

After positioning the cantilever, the magnification of the SEM was increased. Figures 4(d) and 4(e) show the SE image and the image of the summed signals of SE and EBIC, respectively. In Fig. 4(d), the semiconductor region is almost entirely flat. As shown in Fig. 4(e), the region of the high EBIC signal exits within the Si region. Thus, the EBIC signal might be induced by the built-in electric field of the p–n junction. Here, an electric field can induce trapped charges in the surface levels of the semiconductor surface, which results in a broad distribution of EBIC signal.\(^{18}\) Thus, as shown in Fig. 4(e), the EBIC signal distribution was expanded due to these trapped charges. However, it was possible to position the cantilever at the p–n junction using the high EBIC signal. Therefore, using the above positioning method, the cantilever was successfully positioned at the p–n junction of the polished Si-FRD.

C. SPM measurement of the Si-FRD

Figures 5(a)–5(e) show AFM, SCFM, and KFM images of the polished Si-FRD in the same scan area. From the polished Si-FRD whose A and K electrodes were shorted, Figs. 5(a) and 5(b) are obtained simultaneously using AFM and SCFM. Polishing traces a few nanometers in height can be seen in the AFM image, where the arithmetic mean height was estimated to be 0.3 nm. Thus, the surface of the polished Si-FRD was made flat by the CMP process. Signal contrast was observed in the SCFM image. Opposite polarity gradients of the differential capacitance are measured from p- and n-type semiconductors.\(^{23}\) According to this theory, the phase of the SCFM signal of the p-type region might be opposite to that of the n-type region, which results in the contrast of the SCFM image. Thus, the signal contrast in the SCFM image indicated the position of the p–n junction of the polished Si-FRD.

Figure 5(c) shows a KFM image of the polished Si-FRD whose A and K electrodes were shorted. Across the p–n junction of the polished Si-FRD, the surface potential of the p region was smaller than that of the n region. When the potential of the cantilever was grounded, the surface potential measured using the KFM decreased as the work function of the sample became a lager value. Here, in the same semiconductor, the work function of a p-type semiconductor is higher than that of an n-type one.\(^{43}\) Thus, it was reasonable that the surface potential of the p region was smaller than that of the n region in the KFM image. Figures 5(d) and 5(e) show KFM images of the polished Si-FRD under applied bias voltages of ~0.5 and ~1.0 V, respectively. A reverse bias voltage is applied to the p–n junction of an FRD.\(^{44}\) Thus, in the two KFM images, the potential contrasts at the p–n junction increased the applied bias voltage, \( V_{AK} \).
To investigate the SCFM and KFM images in detail, cross sections were obtained from these images, as shown in Fig. 5(f). The cross sections of Figs. 5(b)–5(e) are indicated with dashed lines and labeled i–iv in Fig. 5(f), respectively. As shown in Fig. 5(f), the green dashed line indicates the position of the p–n− junction of the polished Si-FRD. In the cross section of the SCFM signal labeled i, the absolute value of the SCFM signal in the p region was smaller than that in the n− region. If a differential capacitor consisting of a cantilever and a semiconductor is assumed to be a metal-oxide-semiconductor capacitor, a low carrier density region would show a high differential capacitance. An n− layer in an FRD with a p–n− structure is designed as a low-carrier-density layer compared with the p and n layers. 44 Thus, the relationship of the SCFM signals between the p region and the n− region was in qualitative agreement with the expected carrier density distribution of the Si-FRD.

FIG. 5. SPM images of the polished Si-FRD and cross sections obtained from the SCFM and KFM images: (a) AFM image. (b) SCFM image. (c) KFM images. (a)–(c) were obtained from the Si-FRD whose A and K electrodes were shorted. (d) and (e) KFM images with applied bias voltages of −0.5 and −1.0 V, respectively. The dashed lines on the SCFM and KFM images were used to obtain the cross sections. (f) Cross sections of the SCFM and KFM signals from the polished Si-FRD. The p–n− junction is indicated with the green dashed line in (f).
In the cross section of the KFM signal labeled ii, a potential drop was observed. The position of the potential drop corresponds with the position of the p–n junction. In the cross sections of the KFM signals labeled iii and iv, the surface potential on the p region decreased as the applied reverse bias voltage was increased. This region included the p–n junction of the polished Si-FRD. In addition, using SCFM and KFM, the position of the p–n junction was determined with a high spatial resolution compared with the EBIC signal.

As described here, the signal contrasts derived from the structure of the Si-FRD were observed using the AFM/SEM system. In particular, the SCFM signal was found to correspond to the expected carrier density distribution of the Si-FRD. In the future, this AFM/SEM system will be capable of observing a cleavage cross section of a solar cell and evaluating the special junction termination of an Si-FRD.

IV. CONCLUSION

An AFM/SEM system was developed for the evaluation of electronic devices. To maintain the high spatial resolution of the SEM, the working distance of the OBD unit was determined to be 2 cm. The laser beam irradiated the cantilever at an obtuse angle to the sample surface to allow for simultaneous SEM observations of the sample. The scan unit was fabricated using three tube scanners to probe the Si-FRD. The scanning range of the scan unit along the X, Y, and Z axes were 21.9, 23.1, and 2.5 μm, respectively. The noise density in the detection unit was estimated to be 0.29 pm/Hz0.5 by measuring the Brownian motion of the cantilever. The cantilever was exactly positioned at the p–n junction of a polished Si-FRD using the SCFM signal. After positioning the cantilever, the semiconductor region of the polished Si-FRD was probed using AFM, SCFM, and KFM. The position of the p–n junction was determined using SCFM and KFM with a high spatial resolution. When reverse bias voltages were applied to the polished Si-FRD, the potential variations of the p region were in agreement with the applied reverse bias voltages of −0.5 and −1.0 V. Thus, the KFM signals also suggest that the scan area included the p–n junction of the polished Si-FRD. In addition, using SCFM and KFM, the position of the p–n junction was determined with a high spatial resolution compared with the EBIC signal.

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