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Surface potentials on Pd/GaAs contacts studied using scanning probe microscopy

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Abstract. Two Pd/GaAs contacts annealed at different temperatures were evaluated with the current–voltage measurement to be Schottky and ohmic contacts, respectively. Using a scanning probe microscope that is capable of surface potential measurement, we measured the contact potential differences (CPDs) for the Pd/GaAs Schottky contact and confirmed that there is no significant potential barrier for the Pd/GaAs ohmic contact interface. By defining the ohmic electrode on the rear side of the GaAs substrate to be the reference electrode, we observed that the surface potential on the GaAs surface is almost constant and attributed this tentatively to be a result of the CPD between the probe tip and GaAs surface.

When a metal comes into contact with a semiconductor there will be a charge transfer between them because the Fermi levels for the two are normally different, which results in the formation of a potential barrier at the interface. This Schottky barrier is characterized as to rectify the flow of carriers under applied bias voltages. To evaluate the Schottky barrier height, an alloyed interface without rectification effect, i.e., an ohmic electrode, is normally prepared on the other side of the semiconductor substrate. The barrier height can be estimated by the current–voltage (I–V) method in which the electron current variation through the interface is measured with bias voltages applied to the Schottky diode [1].

Recently, scanning probe microscopy (SPM) has been developed to map potential distribution on a surface together with its topography [2]. Contact potential differences (CPDs) measured by this technique between the metal/metal and metal/semiconductor contacts were reported [3, 4]. Surface potentials are measured through detection of electromagnetic force occurring on the probe as a result of a surface potential difference between the tip and the sample surface [2]. The contact potential measurement using SPM is thus quite different from the I–V measurement. In order to clarify this SPM technique for measuring CPDs, we prepared both Schottky and ohmic Pd/GaAs contacts whose electrical properties (barrier heights) were evaluated with I–V measurements.

We have shown a comparison of the surface potential difference between the Pd film and GaAs substrate measured using the SPM technique with the barrier height estimated from the I–V method [4]. In this article we propose to perform quantitative analysis on the surface potential, by defining the ohmic electrode prepared on the rear side of the GaAs substrate as the reference electrode. We prepared two types of Pd/GaAs interfaces by annealing at different temperatures and evaluated them with the I–V measurements to be Schottky and ohmic contacts. We measured surface potentials on the Pd film and GaAs substrate surface for these two types of Pd/GaAs interfaces. We obtained unique information useful for the explanation of the surface potentials measured using the SPM and confirmed that there is no significant potential barrier at an ohmic contact of Pd on GaAs.

1 Experiment

We used a commercial SPM (Digital Instruments, Nanoscope III) that is capable of surface potential measurement simultaneously with topography. A rectangular-shaped silicon cantilever (Nanoprobe) with a metal-coated conductive tip was used. The topography is obtained with the "tapping" mode in which the change of the amplitude of the mechanically oscillated cantilever is used to image the surface morphological feature. The surface potential is measured in an "interleave" scan in which the cantilever is not mechanically oscillated and the tip is lifted up for 100 nm, while an oscillation voltage is applied directly to the tip to measure the surface potential. We have noted that the SPM can measure absolute values of surface potentials with respect to the reference electrode, i.e., the sample holder which is grounded in the SPM system [4]. More information on surface potential measurements, coating of the tip, and measurement conditions was reported elsewhere [4]. An ohmic electrode was first prepared on the rear side surface of an n-type GaAs substrate with indium followed by surface treatments [5]. Pd films of diameter 500 μm

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were prepared by evaporating palladium onto the GaAs surface by resistance heating in a high vacuum. Two Pd/GaAs samples were used in this study. These were prepared by annealing at 250 and 350 °C, respectively, for 15 min. The *I–V* measurements made with an electrometer (Keithley 614) were used to evaluate the electrical properties of the two samples.

2 Results and discussion

We first evaluated the electrical properties of the two Pd/GaAs samples using the *I–V* measurement. The current was recorded with the electrometer when the bias voltage applied on the Pd film, with respect to the ohmic electrode, changed from − 0.6 to 0.6 V. Figure 1 shows *I–V* curves for the two Pd/GaAs samples annealed at 250 °C and 350 °C. For convenience the reverse current was expressed in absolute values. We can see that the Pd/GaAs sample annealed at 250 °C shows Schottky contact characteristics whereas the one annealed at 350 °C shows an ohmic contact behavior. The barrier height estimated from the forward *I–V* curve for the 250 °C-annealed Pd/GaAs sample is 0.81 eV with an ideality factor of 1.18. This value of barrier height for the 250 °C-annealed Pd/GaAs Schottky contact is in good agreement with the typical barrier height for annealed Pd/GaAs Schottky contacts [5]. The interface corresponding to this barrier height is believed to be dominated by a metallic compound of Pd−Ga−As [5]. On the other hand, when the annealing temperature is beyond a certain level, the interface will result in an ohmic contact, as we observed for the 350 °C-annealed Pd/GaAs sample. An ohmic contact indicates the absence of a significant potential barrier between the Pd film and the underlying GaAs bulk [1].

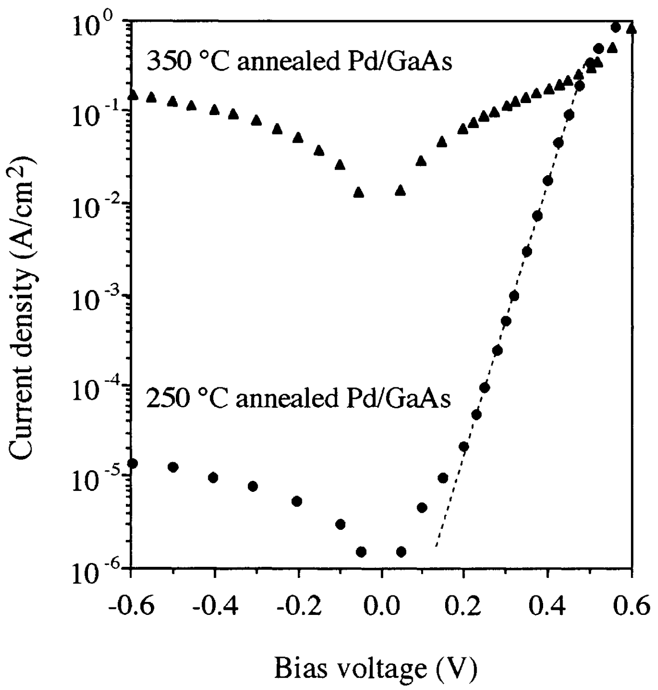

Fig. 1. The current–voltage curves for the Pd/GaAs contact samples annealed at 250 °C and 350 °C. The dotted fine indicates how we estimate the barrier height and ideality factor. The reverse current is expressed in absolute values for convenience

In order to compare the difference between the two Pd films annealed at different temperatures, we imaged the Pd film surface morphology and show the results in Fig. 2 for both Pd/GaAs samples. The 250 °C-annealed Pd film shows nanometer-scale particles. On the other hand, the 350 °C-annealed Pd film is completely crystallized. Although

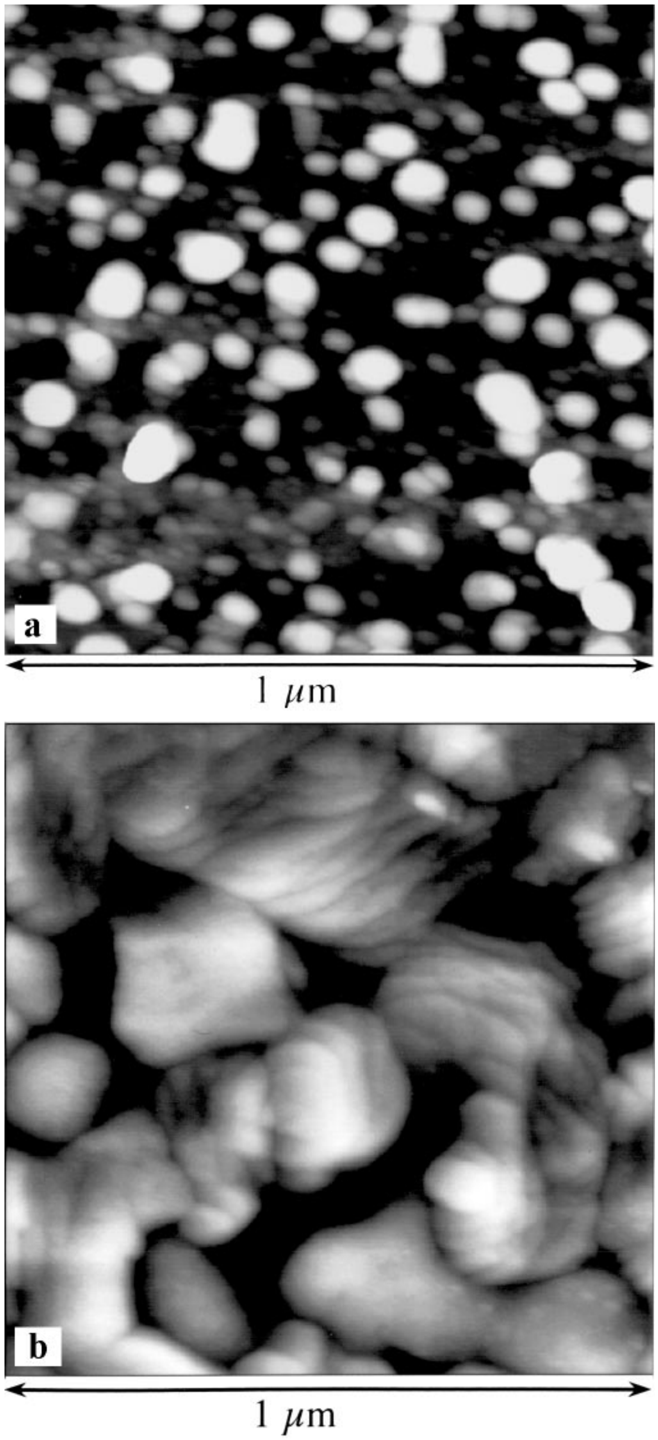

Fig. 2a,b. Topographic images for the surfaces of the two Pd films annealed for 15 min **a** at 250 °C and **b** at 350 °C, respectively. The scan area is 1 μm × 1 μm and the gray scale is from 0 to 25 nm for the two images

Pd/GaAs interfaces could not be imaged, at least we obtained two types of Pd/GaAs interfaces based on both the electrical properties in Fig. 1 and surface features in Fig. 2.

In this study we aim to address the surface potential on the Pd contact and the GaAs substrate surface with respect to the ohmic electrode. We therefore first checked the reference electrode in the SPM system. The reference electrode is the grounded sample holder whose surface potential should be, at least in principle, 0 V. The surface potential on the reference electrode was confirmed to be around 0.05 V by measuring a fresh gold film prepared on the sample holder surface. Conductive paste used to glue the sample on the sample holder, i.e., the reference electrode, was also confirmed to have a surface potential of about 0.1 V. By using this conductive paste, the ohmic electrode of the Pd/GaAs sample was glued on the sample holder. This configuration ensured that the ohmic electrode of the Pd/GaAs sample can be considered as the reference electrode within an uncertain quantity of 0.1 V.

Figure 3 shows a typical topography (a), and surface potential image (b), for the Pd/GaAs Schottky contact sample in a 200 μm square in which both the Pd film and GaAs surface are included. A small part of the Pd film is shown in Fig. 3a as the brighter part and the rest is the GaAs surface. Figure 3b shows a surface potential distribution on the same area as shown in Fig. 3a in which the bright corresponds to 1.1 V while the dark to 0.4 V.

A profile for the surface potential across the Pd film and GaAs surface is shown as curve (a) in Fig. 4. The surface potentials on the Pd film and the GaAs surface were measured to be approximately 0.40 V and 1.06 V with respect to the reference electrode. The difference between these two surface potentials, i.e., 0.66 V, is attributed to the contact potential between the Pd film and GaAs surface [4]. The two surface potentials themselves are, as far as we know, not reported because a well-defined reference electrode is needed. In order to clarify the origins of the two potential differences observed on the Pd film and the GaAs surface for the Schottky contact, we propose to measure possible changes in the surface potentials on the Pd film and GaAs surface by connecting the Pd film

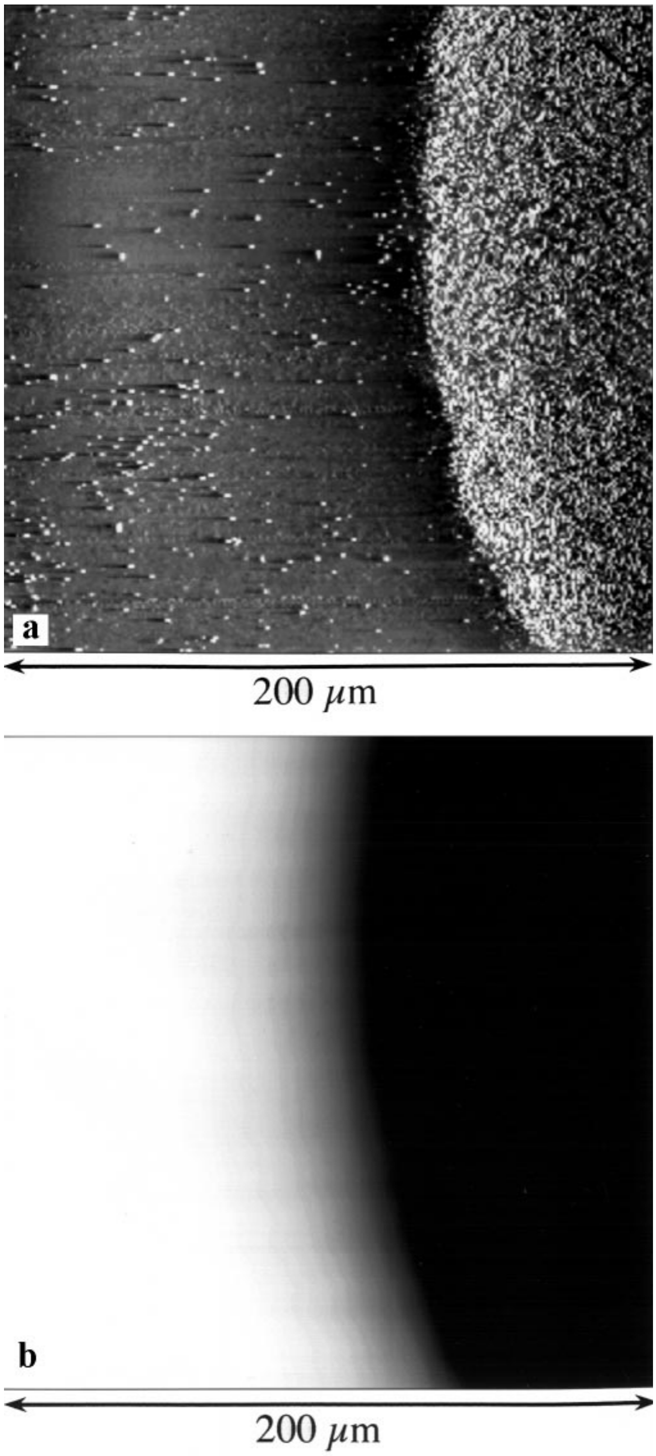

Fig. 3a,b. Topography (**a**) and surface potential image (**b**) obtained simultaneously on a Pd/GaAs Schottky contact sample surface. The scan area is 200 μm × 200 μm. The gray scales are from 0 to 200 nm and 0.4 to 1.1 V, respectively

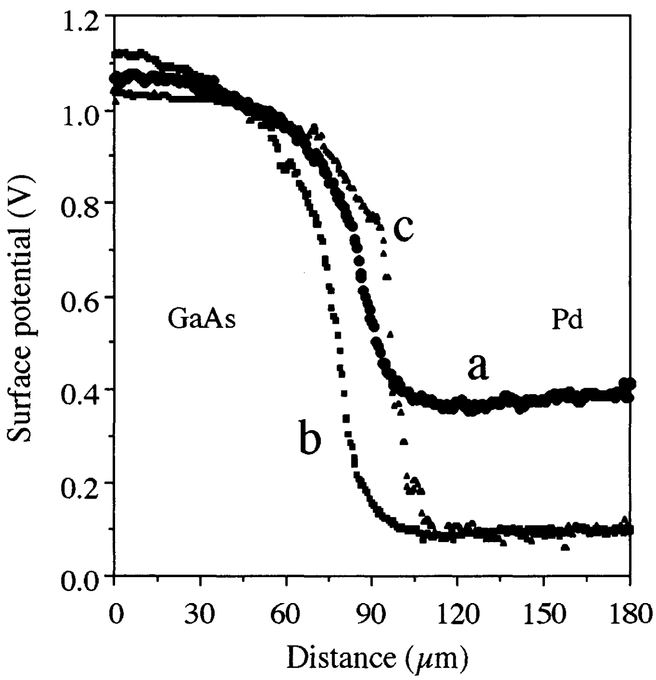

Fig. 4. Profiles for the surface potentials across the GaAs substrate and Pd film for (a) the Schottky contact Pd/GaAs sample, (b) the Schottky contact with the Pd film grounded, and (c) the ohmic contact Pd/GaAs sample

electrically with the reference electrode using the conductive paste.

After grounding the same Pd film, the surface potentials were measured and are shown as curve (b) in Fig. 4. We can see that the surface potential on the Pd film decreased to 0.1 V, which is close to that of the ohmic electrode by considering the experimental uncertainty as described above. This is expected because grounding the Pd film will force its surface potential to be equal to that of the reference electrode. On the other hand, the surface potential on the GaAs surface is almost unchanged by the measuring configuration, considering the experimental uncertainty for the surface potential measurement was about 0.1 V.

We imagined that if the Pd/GaAs contact is an ohmic one the potential difference between the Pd film and the ohmic electrode (reference electrode) will be close to 0 V. We confirmed this by measuring surface potential differences between the Pd film and the GaAs surface for the Pd/GaAs ohmic contact sample (whose *I*–*V* characteristics are shown in Fig. 1). The result is shown as curve (c) in Fig. 4, in which the surface potential on the Pd film is close to that of the reference electrode. Unlike the grounded Pd film in the Schottky contact sample, because there is no external conductive connection to the reference electrode for the Pd film in this ohmic contact sample, we can conclude that the Pd film is almost at the same potential with respect to the ohmic electrode. This experimental result is instructive for demonstrating that an ohmic contact means the absence of a significant contact barrier at the metal/semiconductor interface [1].

As shown in curves (b) and (c) of Fig. 4, the difference between the surface potentials on the Pd film and GaAs surface for the Schottky contact sample when grounding the Pd film and for the ohmic contact one increased to about 1.0 V. This value of 1.0 V, however, should not be considered as the CPD between the Pd film and GaAs surface, because the Pd film is electrically connected with the reference electrode owing to grounding for the Schottky contact sample or to the absence of a potential barrier for the ohmic contact one.

As described above, the surface potential observed on the Pd film depends on the electrical properties (barrier height) of the Pd/GaAs interface and measuring configuration, whereas the surface potential observed on the GaAs surface is almost constant. We tentatively attribute this potential to be the CPD between the probe tip and the GaAs surface. In this case, the CPD between the tip and GaAs surface is mainly determined by their effective work functions [6]. Unlike the surface potential on the Pd film, which is related to the barrier height at the interface as well as the ohmic electrode, the CPD between the tip and GaAs surface is insensitive to the measuring configuration.

3 Conclusions

We measured surface potentials on Schottky and ohmic contact Pd/GaAs samples which were evaluated with *I*–*V* measurements. By connecting the ohmic electrode of the Pd/GaAs Schottky sample electrically to the sample holder, which is grounded in the SPM system, we measured potential differences both on the Pd film and GaAs surface with respect to the ohmic electrode. For the Schottky contact Pd/GaAs interface, the difference in surface potential between the Pd film and GaAs substrate is a reflection of the barrier height. For the ohmic contact Pd/GaAs interface we confirmed that there is no significant potential barrier present at the interface. The surface potential on the GaAs surface is constant and is tentatively attributed to be a result of the contact potential difference between the tip and GaAs surface.

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