Resistance measurements of metallic silicide nanowires on a Si substrate with a four-tip scanning tunneling microscope *

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(Received 12 October 2005; Accepted 22 November 2005; Published 3 December 2005)

We have measured electrical resistance of individual epitaxial CoSi₂ nanowires (NWs) formed on a Si(110) surface *in situ* in ultrahigh vacuum, by two-, three-, and four-point probe methods using a multi-tip scanning tunneling microscope at room temperature. The NWs were electrically isolated from the substrate by a Schottky barrier in-between with zero-bias resistance of approximately $10^7 \Omega$. Contact resistance between a W tip and a NW was as small as several tens Ω . The resistivity of the NWs was ca. $30 \mu\Omega\text{cm}$, which is similar to that of high-quality epitaxial CoSi₂ films. The oxidation of the NW surface had negligible influence on the resistance, meaning marginal carrier scattering at the NW surface.

[DOI: 10.1380/ejsnt.2005.362]

Keywords: Nano-wires; Multi-probe method; Electrical transport; Cobalt; Silicides; Si(110); Multi-tip scanning tunneling microscope

I. INTRODUCTION

Nanowires (NWs) have attracted much attention recently as promising elements for future nano-scale devices [1, 2] as well as for one-dimensional physics. Among various synthetic methods, self-assembly methods such as reactive deposition epitaxy (RDE) and catalytic growth are suitable for mass production [3–11]. Therefore, it is important to characterize properties of self-assembled NWs. The technological aspects and physical properties such as transistor action and coulomb blockade phenomena have been investigated *ex situ* [12–16] at low temperature and under high magnetic field. Such *ex situ* measurements allow determination of fundamental transport parameters, but they inherently contain a problem of possible degradation of sample during air exposure and fabrication of contact leads, which can obscure the intrinsic behaviors of NWs. To avoid such disadvantages of the *ex situ* measurements, we have demonstrated here *in situ* resistance measurements by using a multi-tip scanning tunneling microscope (STM). CoSi₂ NWs of about 60 nm wide were formed on a Si(110) substrate by RDE in ultrahigh vacuum (UHV). We performed all of the possible electrical measurements with the four-tip STM *in situ*, and then determined the resistivity of NWs and contact resistance between the W tip and NW. A two-point probe (2PP) method was performed on the NWs and Si substrate surface at first. Then, a three-point probe (3PP) method was performed on a single NW to extract the contact resistance. And then, a four-point probe (4PP) method was performed on a single NW, which enabled measurements without contact-resistance problem. Finally, the 2PP method with changing the probe separation was per-

formed on single NWs. This paper is an extension of our previous work [17] by adding the 3PP measurements and fully comparing the results of all kinds of multi-probe measurements.

From these measurements, it is clarified that the transport through the NWs of several microns long is diffusive at room temperature with a resistivity (ca. $30 \mu\Omega\text{cm}$) similar to that of epitaxial CoSi₂ thin films. And the NWs were found to be electrically well isolated from the substrate by a Schottky barrier in-between with zero-bias resistance of approximately $10^7 \Omega$, which prevents the measuring current through the NW from leaking into the substrate. The contact resistance between the W-STM tip and a NW was several tens Ω , which is less than 10% of the resistance of NWs several microns long. The resistivity of NWs was essentially unchanged after exposure to air, suggesting negligible influence of surface scattering.

II. EXPERIMENTAL

The substrate was a *p*-type Si(110) wafer with resistivity of $1 \Omega\text{cm}$. The Si(110) substrate was cleaned by resistively heating to 1200°C in UHV. Self-assembled CoSi₂ NWs of about 60 nm wide were formed just by sublimation of high-purity cobalt of 99.99+% onto the Si(110) substrate held at 750°C in a UHV chamber of the four-tip STM. The typical deposition rate was 1 ML in 10 min. The NWs are single-crystalline epitaxial silicide [10]. The resistance measurements were performed *in situ* at room temperature using a homemade four-tip STM with independent motion of the tips [18–21]. The arrangement of tips can be monitored using an integrated UHV field-emission scanning electron microscope (FESEM) column. Electrical contact with the NWs or Si substrate surface was made by making the electrochemically etched W tips move forward one step (approximately 10 nm) beyond the point of tunneling using a piezo-actuator. The tips sometimes became damaged after repeating contacts, but they could be easily exchanged using a load-lock system.

*This paper was presented at International Symposium on Surface Science and Nanotechnology (ISSS-4), Saitama, Japan, 14–17 November, 2005.

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III. RESULTS

Results by the 2PP method are shown first. Figure 1(a) shows a SEM image with two STM tips contacting a single NW. The NWs in the image are typically 60 nm wide and 5 μm long. 2PP current-voltage (I - V) curves were measured between various pairs of contact points as indicated in the figure. For the pair of points A and B in which both tips are on a single NW, the resulting I - V curve is linear up to 500 μA , as shown in the inset in Fig. 1(b). The resistance is 610 Ω for a probe spacing of 2.8 μm , corresponding to a resistance per length $R/l = 220 \pm 30 \Omega/\mu\text{m}$ (by neglecting the contact resistance at the tip contacts). For the pair of points C and D in which both tips contact the substrate, the I - V curve is nonlinear as shown in Fig. 1(b). Saturation voltages at 10 μA and at -10 μA are slightly different. This asymmetry is caused by difference in contact condition such as contact area and Schottky barrier height between at contact points C and D. For the pair of contact points A and C in which one of the tip is on a NW and another is on the substrate, similar asymmetric nonlinear I - V curves are observed. The case for the pair of A and E in which the two tips are on different NWs, give a similar result. The differential resistance at $V = 0$ obtained from these nonlinear I - V curves is approximately $10^7 \Omega$. As discussed in the next section, these nonlinear I - V curves mean that there exist Schottky barriers between the NW and substrate as well as between the tip and substrate. It is clear that conduction through the substrate can be ignored in comparison with conduction through a NW because of large difference in measured resistance.

It was difficult to judge good alignment of the tips contacting the NWs just by the SEM images, because the end of tip was usually much larger than the width of NWs and easily hid NWs. Hence, positioning of the tips on a NW had to be confirmed by a low resistance value.

The 2PP measurement contains unknown series contact resistance between the tips and the NWs. The contact resistance can be obtained by comparing with the results of 3PP measurement as shown in Figure 2. The 3PP resistance V_{12}/I_{13} (or V_{23}/I_{13}) was obtained by passing the current through the outer pair of probes 1 and 3, and measuring the voltage drop between the probe 1 and probe 2 (or between the probe 3 and probe 2). V_{12}/I_{13} includes the NW resistance between tip 1 and tip 2 and contact resistance at tip 1 as well. By comparing V_{12}/I_{13} with the 2PP resistance V_{12}/I_{12} which contains the contact resistance at tip 2 in addition to the NW resistance and the contact resistance at tip 1, the contact resistance at tip 2 can be extracted. For probe spacing of 1.4 μm between tip 1 and 2, and probe spacing of 3.2 μm between tip 2 and 3 on a single NW, the measured 2PP and 3PP resistances are shown in Table I. Then the contact resistance at tip 2 ($V_{12}/I_{12} - V_{12}/I_{13}$ or $V_{23}/I_{23} - V_{23}/I_{13}$) was 40~60 Ω . The contact resistance obtained by the same method at other contact points was sometimes larger than this value because the contact resistance depends on contact area and contact condition. Therefore, this value was a typical value when good contacts were formed.

The contact resistance between the tip and NW can be fully avoided by using 4PP method as shown in Figure

FIG. 1: (a) A SEM image at 2PP measurements with various pairs of contact points as marked by letters. (b) I - V curves for two tips on the substrate (points C and D), for one tip on the substrate and the other on a NW (points A and C), and for one tip on a NW and the other on another NW (points A and E). The inset is a magnified I - V curve between two tips on a single NW (points A and B).

TABLE I: 2PP and 3PP resistances of the NW in Fig. 2.

3PP resistances (Ω)	$\frac{V_{12}}{I_{13}} = 718$	$\frac{V_{23}}{I_{13}} = 1210$	
2PP resistances (Ω)	$\frac{V_{12}}{I_{12}} = 781$	$\frac{V_{23}}{I_{23}} = 1250$	$\frac{V_{13}}{I_{13}} = 1900$

3. The 4PP resistance V_{23}/I_{14} was obtained by passing the current through the outer pair of probes (tip 1 and tip 4) and measuring the voltage drop between the inner pair of probes (tip 2 and tip 3). Since the current flowing through the voltage (V_{23}) measurement circuit is negligible, the V_{23} does not contain the voltage drop due to the contact resistance at tips 2 and 3. Such a 4PP measurement was done for different probe spacings between the inner probes (tips 2 and 3), as shown in Table II. The resistance per length R/l is then obtained straightforwardly to be $220 \pm 50 \Omega/\mu\text{m}$ from the 4PP results, which agrees well with the result of 2PP measurement in Fig. 1. The difference between the 2PP resistance and 4PP resistance comes from the contact resistance, which is found to be 30~40 Ω . This value of contact resistance is similar to

FIG. 2: A SEM image and $I - V$ curves at 3PP measurement. The current was made pass through the tip 1 and tip 3, and the voltage drop was measured between the tip 1 and tip 2, or between tip 2 and tip 3.

that obtained from the 3PP method mentioned before. Thus we can say that the contact resistance at the tip contacts is several tens Ω at good contact, which is less than 10% of the resistance of several-microns long NWs.

It is also possible to determine the resistance per length of a NW and the contact resistance using the 2PP measurement by taking a series of data with changing the probe spacing [22–24]. By assuming diffusive transport through the NW, the 2PP resistance R can be written by

$$R = \rho \frac{l}{S} + R_C, \quad (1)$$

where R_C is a sum of the contact resistances between the W tips and the NW at both ends, and l , S , and ρ are the tip separation, cross section and resistivity of the NW, respectively. The data are shown in Figure 4 as a function of l , which includes results from several different NWs. The data with the smallest resistance at each l (red circles in Fig. 4) was fitted by Eq. (1), because larger resistances were due to poor contact (larger R_C). The data-fit (dotted line) yields $R[\Omega] = (210 \pm 30) \times l[\mu m] + (30 \pm 60)$. Within the uncertainties, this result agrees well with the 4PP measurement mentioned before. It should be noted that these 2PP measurements actually were done on samples that had been intentionally exposed to air, while the 4PP measurements were done *in situ* in UHV. Therefore, the agreement between them indicates a negligible effect of oxidation. We return to this point in the next section.

FIG. 3: A SEM image and an $I - V$ curve at the 4PP measurement. The current was passed through the tip 1 and 4, and the voltage drop was measured between the tip 2 and 3.

TABLE II: 2PP and 4PP resistances of the same NW.

Probe spacing (μm)	4PP resistance (V_{23}/I_{14}) (Ω)	2PP resistance (V_{23}/I_{23}) (Ω)
1.5 ± 0.2	309	351
0.9 ± 0.2	207	237

IV. DISCUSSION

Metallic NWs can be used as electrical interconnects and nanoelectrodes. For this purpose, the NWs must have low resistivity and good electrical isolation from the substrate. In the 2PP measurements, the $I - V$ curves were nonlinear as shown in Fig. 1 when one of the tips was on the substrate or two tips were on different NWs. The curve is explained in terms of head-on double-diode circuit, which means that Schottky barriers are formed at both of the tip-substrate contacts and NW-substrate interface [25]. Therefore, the NWs are electrically isolated from the substrate by the Schottky barrier whose reversed-bias resistance is as high as ca. $10^7 \Omega$. On the other hand, the contact between the tip and NW is ohmic because W tips and the NWs are metallic, which produces the contact resistance as small as several tens Ω when good contact was formed. This is surprising because the contact resistance had been expected to be much larger due to small contact area on the order of several hundreds

FIG. 4: 2PP resistance measured with changing the probe spacing for an air-exposed sample. Dotted line is a fit by Eq. (1) with data in red, giving a resistance per length $210 \pm 30 \text{ } \Omega/\mu\text{m}$.

nm^2 .

The resistivity of the NW may now be calculated, provided one knows the NW cross-section. The width can be determined from FESEM images, while the height is determined from cross-section Transmission Electron Microscopy (TEM) images [10]. The averages in width and height of our NWs were found to be approximately 60 and 40 nm, respectively. Thus, we obtain a resistivity $\rho = 31 \pm 9 \text{ } \mu\Omega\text{cm}$. The net uncertainty includes 10% in both width and height, as well as 15% in the R/l value obtained in the present study.

This value of resistivity is comparable but somewhat higher than that of molecular beam epitaxy-grown films of CoSi_2 on Si substrate, for which $\rho \sim 15 \text{ } \mu\Omega\text{cm}$ at 300K [26]. The *residual* resistivity (measured at 4K) of films can be much smaller, and depends sensitively on the quality of the sample. The TEM images and the epitaxial nature of the growth suggest that the NWs are essentially perfect single crystals, hence, should have resistivity similar to that of high-quality films. One might expect an excess resistance due to inelastic scattering at the NW boundaries (buried interface and exposed surface). Von Känel, *et al.* have measured and modeled this effect for ultrathin epitaxial CoSi_2 films on Si(111), and found an excess (surface) resistivity that scales with film thickness, with typical values of $\rho_{\text{surf}} \sim 10 \text{ } \mu\Omega\text{cm}$ for 3 nm thickness [27]. The interface scattering will depend sensitively on the structure of the interfaces. In our experiment, this

was tested directly by comparing the NW resistance before and after oxidation. We found no change within 30% uncertainty. Therefore, phonon scattering seems to dominate the resistance for 60 nm thick NWs rather than the surface scattering. This should be, however, confirmed by measuring the temperature dependence of NW resistivity with a variable-temperature four-tip STM [28], which is a future subject.

One may also compare our value of resistivity with that of metallic NWs fabricated by other means. It is $\rho \sim 12 \text{ } \mu\Omega\text{cm}$ for buried CoSi_2 wires [29], $17.1 \text{ } \mu\Omega\text{cm}$ for 60 nm diameter Cu [25], $33 \pm 5 \text{ } \mu\Omega\text{cm}$ for 70 nm diameter Pt [23], and $4.5 \text{ } \mu\Omega\text{cm}$ for 70 nm diameter Au NWs [22]. In these cases, the resistivity will depend sensitively on the size and quality of the NW. We note a recent report for chemical-vapor deposition-grown NiSi NWs, giving $\rho = 9.5 \text{ } \mu\Omega\text{cm}$ for 30 nm diameter at 4 K [30]. Lowering temperature reduces phonon scattering of carriers, but this value is remarkably small, nonetheless, implying a nearly perfect crystal structure and weak interface scattering.

V. CONCLUSION

In summary, owing to the capability of positioning four-tip probes arbitrarily in the four-tip STM, we have demonstrated two-, three-, and four-point probe measurements of resistance of individual CoSi_2 NWs formed on a Si(110) surface at room temperature. The results show that simple preparations such as deposition and annealing create good metallic and self-assembled NWs on the silicon surface. The NWs have a low resistivity similar to that of the high-quality epitaxial film even after exposure to air. In addition, since the NWs are electrically isolated from the substrate due to the Schottky barrier in-between, they are promising candidates for conductive nano-electrodes in future electronic devices.

Acknowledgments

The authors wish to thank Zhian He and David J. Smith for valuable discussions about the structure of CoSi_2 NWs. This work has been supported by Grants-In-Aid from Japanese Society for the Promotion of Science.

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