APPLIED PHYSICS LETTERS **86**, 233108 (2005)

In situ resistance measurements of epitaxial cobalt silicide nanowires on Si(110)

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(Received 21 March 2005; accepted 10 May 2005; published online 3 June 2005)

We have performed *in situ* resistance measurements for individual epitaxial $CoSi_2$ nanowires (NWs) (approximately 60 nm wide and 5 μm long) formed on a Si(110) surface. Two- and four-point probe measurements were done with a multitip scanning tunneling microscope at room temperature. The NWs were well isolated from the substrate by a Schottky barrier with zero-bias resistance of 10^7 Ω. The resistivity of the NWs was 30 $\mu\Omega$ cm, which is similar to that for high-quality epitaxial films. The NW resistance was essentially unchanged after exposure to air. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1948519]

Nanowires (NWs) have received much attention recently as promising elements for future nanoscale devices.[1,2] Semiconducting NWs can be used as active electric elements, and transistor action has been reported.[3–5] Metallic NWs are suitable as electrical interconnects or nanoelectrodes. For the latter purpose, the NWs must have low resistivity and good electrical isolation from the substrate. Recently, it has been reported that self-assembled single-crystal epitaxial silicide NWs can be formed by simple deposition of metal onto a heated silicon surface in UHV.[6–13] The resistance of metallic NWs has been measured for some cases *ex situ*.[14,15] *Ex situ* measurements done at low temperature and high magnetic field allow determination of fundamental transport parameters, but they inherently contain a problem of possible sample transformations during air exposure and fabrication of contact leads which can obscure the intrinsic behavior.

In this letter, we report *in situ* resistance measurements of individual epitaxial NWs using a multitip scanning tunneling microscope (STM). The intrinsic NW resistance is separated from the contact resistance using a distance-dependent two-point probe method or a four-point probe method. The NWs are very well isolated from the substrate by a Schottky barrier with zero-bias resistance of 10^7 Ω. The resistivity of 60 nm wide NWs was 30 $\mu\Omega$ cm and was essentially unchanged after exposure to air, suggesting a negligible influence of interface scattering. Development of the multitip STM will enable *in situ* transport measurements for a wide variety of surface nanostructures.

$CoSi_2$ NWs were formed by sublimation of high-purity cobalt onto Si(110) held at 750 °C in UHV. The typical deposition rate was 1 ML in 10 min. The resistance measurements were performed at room temperature using a homemade four-tip STM with independent motion of the tips.[16–18] The arrangement of tips can be monitored using an integral UHV field-emission scanning electron microscope (FESEM) column. Electrical contact with the NWs or Si surface was made by moving the electrochemically etched W tips one step (approximately 10 nm) beyond the point of tunneling. The tips sometimes became damaged after multiple contacts, but they could be easily replaced using a load-lock system.

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. Two-point I–V curves were measured between pairs of positions as indicated in the figure. For points A–B, both tips are on a single NW, and the I–V curve is linear, as shown in the inset in Fig. 1(b). The resistance is 610 Ω for a probe spacing of 2.8 μm, corre-

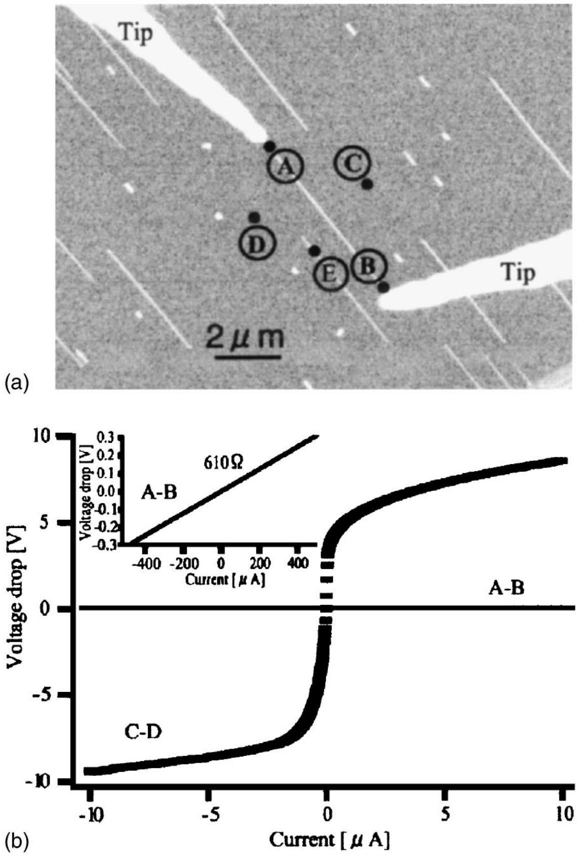

FIG. 1. (a) A SEM image of two-point measurements with pairs of contacts as marked by letters. (b) I–V curves for two tips on the substrate (points C–D), and (inset) for two tips on a single NW (points A–B).

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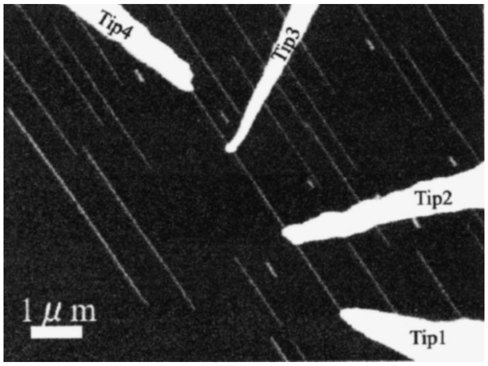

FIG. 2. A SEM image of a four-point probe measurement. The current was passed through the tip 1 and 4, and the voltage drop was measured between the tip 2 and 3.

sponding to a resistance per length of $R/l = 220 \pm 30\ \Omega/\mu\text{m}$. For points C–D, both tips contact the substrate, and the *I–V* curve is nonlinear, as shown in Fig. 1(b). The double-diode behavior reveals that Schottky barriers were formed at both tip-substrate contacts.[19] For points A–E, where the two probes are on different NWs, a similar double-diode curve is observed (not shown), due to the Schottky barriers between the NWs and the substrate. The resistance at $V=0$ obtained from these curves was approximately $10^7\ \Omega$. We note in passing that the Schottky barrier of the NW on the substrate is a very interesting problem itself, and will be reported elsewhere. It is clear that conduction through the substrate can be ignored in comparison with conduction through a NW. It can be difficult to judge good alignment of the tips with the NWs based on the FESEM images, since the tips are larger than the NWs and also obscure them. Hence, good placement of the tips must be confirmed by a low resistance value.

The two-point resistance measurement contains an unknown series contact resistance between the tips and the NWs. This can be removed using a four-point probe measurement as shown in Fig. 2. The four-point probe resistance V_{23}/I_{14} was obtained by passing the current through the outer pair of probes (1 and 4) and measuring the voltage drop between the inner pair of probes (2 and 3). This was done for two different spacings between the inner probes (2 and 3), as shown in Table I. R/l is $220 \pm 50\ \Omega/\mu\text{m}$. The difference between the two-probe and the four-probe values is due to the contact resistance, which is found to be 30–40 Ω for the combined contacts at tips 1 and 4. This shows that the contact resistance is much smaller than the NW resistance, for this experiment.

It is also possible to isolate the contact resistance using a two-point probe measurement, by taking a series of data with a range of probe separation.[20–22] Thus, the two-probe resistance R can be written as

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

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 the length, cross section, and resistivity of the NW. This assumes transport in the diffusive regime—indeed a linear behavior will demonstrate it. The data are shown in Fig. 3, and include results from several different NWs. Only points that showed a linear *I–V* curve with small resistance are shown, which excludes points with poorly positioned tips. The data-fit (dotted line) yields $R[\Omega] = (210 \pm 30) \times l[\mu\text{m}] + (30 \pm 60)$. This result agrees with the four-point measurement within the uncertainties. It should be noted that these measurements actually were done on samples that had been intentionally exposed to air, indicating a negligible effect of oxidation. We return to this point later.

TABLE I. Two and four-point probe resistances of the same NW.

Probe spacing (μm) between tip 2 and 3	Four-probe resistance (Ω)	Two-probe resistance (Ω)
1.5±0.2	309	351
0.9±0.2	207	237

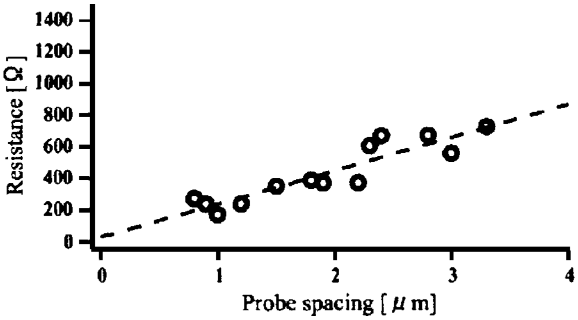

FIG. 3. Two-probe resistance measured with changing the probe spacing for an air-exposed sample. Dotted line is a fit to Eq. (1).

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.[12] The average dimensions were found to be 60 and 40 nm, respectively. Thus, we obtain a resistivity of $31 \pm 9\ \mu\Omega\,\text{cm}$. The net uncertainty includes 10% in both width and height, as well as 15% in the R/l value earlier.

This value of resistivity is comparable but somewhat higher than that of molecular beam epitaxy-grown films of CoSi_2 on Si, for which $\rho \sim 15\ \mu\Omega\,\text{cm}$ at 300 K.[23] The *residual* resistivity (measured at 4 K) 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 crystal structures, 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 $\rho_{\text{surf}} \sim 10\ \mu\Omega\,\text{cm}$ for 3 nm thickness.[24] This effect is expected to be small for the 60-nm-thick NWs. 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 the 30% uncertainty. This likely reflects the limited depth of the interface scattering (3 nm) compared with the NW width (60 nm).

One may also compare our value of resistivity to that of metallic NWs fabricated by other means. Thus, $\rho \sim 12\ \mu\Omega\,\text{cm}$ for buried CoSi_2 wires,[25] 17.1 $\mu\Omega\,\text{cm}$ for 60 nm diameter Cu,[19] $33 \pm 5\ \mu\Omega\,\text{cm}$ for 70 nm diameter Pt,[21] and 4.5 $\mu\Omega\,\text{cm}$ for 70 nm diameter Au NWs.[20] In each case, 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 $\rho = 9.5\ \mu\Omega$ cm for 30 nm diameter at 4 K.[14] The low temperature removes thermal scattering, but this value is remarkably small, nonetheless, implying a nearly perfect crystal structure and weak interface scattering.

In summary, owing to the capability of positioning four-tip probes arbitrarily, we have demonstrated two- 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, which have a low resistivity 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 components of future electronic devices.

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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