Electron transport through indium atomic chain arrays self-assembled on a silicon surface

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Abstract

We clarify electron conduction through indium atomic chain arrays self-assembled on a clean silicon surface. The conductivity of indium chain arrays is extracted through the comparison of two surface structures, one of which includes intentionally introduced defects in the middle of chains. It exhibits a sudden significant drop around 130 K with decreasing temperature, revealing a metal-insulator phase transition. The influence of the finite domain size of the indium chains is discussed.

Key words: atomic chains; electron transport; self-assembling; metal-insulator transition

1. Introduction

The study on intrinsic electron transport through one-dimensional (1D) metal wires fixed on a substrate has been a challenge despite its fundamental importance. This is because the Fermi wavelength of a metal is generally in the order of the atomic distance and the present lithographical technique does not allow fabricating defect-free wires with such small dimensions. In this respect, the self-assembling technique is ideal to fabricate high-quality nanowires or atomic wires. To date, several kinds of metal atomic wires have been fabricated on a semiconductor surface via this approach.[1,2] However, their electron transport properties have not been clarified yet, mainly due to the difficulty in connecting them to electrodes.

In this paper, we reveal electron conduction through indium atomic chain arrays self-assembled on a clean Si(111) surface. The chains are only a few atoms wide and have atomically well-defined structures (see Fig. 1(a) for their structure model).[3] The electronic states of the chains are essentially distinct from those of bulk indium due to complete structural reconstruction including the top layer atoms of the silicon substrate. They develop into the periodic arrays of chains during growth, but are known to maintain the 1D nature of the electronic states.[4]

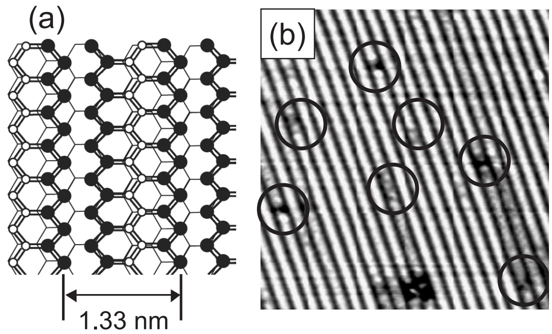

Fig. 1. (a) Structural model of the periodic arrays of indium atomic chains on a Si(111) surface proposed by Bunk *et al.*[3] The filled circles show indium atoms, and the open ones silicon atoms. The period of the chain arrays is 1.33 nm. (b)STM image (27 nm × 27 nm) of indium atomic chains with intentionally introduced defects. The defect structures in the chains are indicated by open circles

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2. Experiment

All experiments are performed under ultrahigh vacuum (UHV) conditions. Two tantalum electrode pads separated by 1 mm are deposited beforehand on a Si(111) substrate with an electron beam evaporator. After loading into the UHV chamber, the sample is flash-cleaned at 1150 °C, onto which indium atoms are deposited to monolayer thickness. Then indium atomic chains are assembled on the substrate by annealing around 450 °C. Scanning tunneling microscope (STM) imaging confirms growth of indium chains up to the edge of the tantalum electrode, essential for transport measurements. The domain size of indium chain arrays is also estimated via STM observation. *In situ* dc two-probe measurements are conducted between room temperature and 6 K. The current-voltage characteristics are linear for $-1\text{V} < V < 1\text{V}$ over a wide temperature range, confirming the absence of a Schottky barrier at the electrode interfaces.

3. Results and Discussions

Although the carriers in the substrate are quenched due to negligible doping concentration below 220 K, there still remains large conduction through the subsurface space charge layer. To extract the conductivity of the surface indium chain arrays, the contribution of the subsurface space charge layer is subtracted as follows. First, pristine indium atomic chains are prepared, and the conductivity of the sample is measured as a function of temperature. After returning to room temperature, a small amount of indium (less than 0.1 ML) is additionally deposited. This process introduces defect-like structures in the middle of the indium chains (Fig. 1(b)). These "defects" work as potential barriers for electrons running through the chains, effectively suppressing the conductivity of the surface atomic chains. The conductivity of the same sample is measured again to be compared with the first measurement. Because the conductivity obtained in the second measurement is attributed only to the space charge layer conduction,[5] the difference of the two gives the conductivity of the surface indium chains.

The conductivity of the atomic chain arrays is plotted as a function of temperature in Fig. 2 (solid line). The average domain size of this sample is estimated to be 70 nm. It exhibits a sudden significant drop around 130 K, clearly indicating the presence of a metal-insulator transition. This is consistent with a previous photoelectron spectroscopy study, which attributed the origin of the phase transition to the Peierls instability.[6] However, the temperature dependence of the conductivity significantly deviates from the behavior

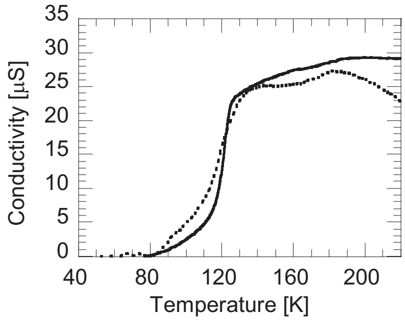

Fig. 2. Conductivity of the indium atomic chain arrays measured as a function of temperature. The estimated average domain size is 70 nm (solid line) and 16 nm (dotted line)

expected from the mean field theory of the Peierls transition. Even in the metallic regime ($T > 130$ K), the conductivity gradually decreases with decreasing temperature. Below 120 K, it asymptotically approaches zero, being observable at least down to 80 K. These two facts suggest the presence of strong thermal fluctuation intrinsic to the 1D system.[7]

The behavior of the phase transition can be influenced by the domain size of the chain arrays. Because growth of indium chains is terminated at surface steps, domains are reduced in size on a highly stepped surface. Figure 2 (dotted line) shows the conductivity of indium chains grown on a highly stepped surface whose averaged domain size is estimated to be 16 nm. Evidently, finite domain size results in a less sharp phase transition. In addition, rather complicated change in conductivity is visible at some points. Superposition of different temperature dependences corresponding to domains with various sizes may explain this behavior.

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