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研究課題名（和文） その場TEM測定による10nm世代Siトランジスタの移動度に及ぼす歪み効果の解明

研究課題名（英文） Investigations of the strain effects on the mobility of 10-nm Si transistors by in situ TEM

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研究成果の概要（和文）：一次元ナノ構造体の電気デバイスが製造されており、それらの機械的および電気的特性は、その場TEM観察法を使用して研究されてきた。シリコンナノワイヤの電子移動度は、引張ひずみ3.4%の下で3.8倍に向上させることができ、14.7%までの曲げひずみの下では2.7倍直線的かつ可逆的に増加させることができた。加うるに提示されたようなキラリティー依存の輸送特性を持ち、約1ナノメートル径を有する単層カーボンナノチューブのトランジスタ及び真空管の製造に成功している。さらに、極限的に高い柔軟性を示し、高性能で柔軟な電子デバイスのための道を切り開くため、原子スケールでの薄い二次元結晶の変形が研究されてきた。

研究成果の概要（英文）：Electrical devices of one-dimensional nanostructures have been fabricated, and their mechanical and electrical properties have been investigated by using the in situ TEM method. The electron mobility of silicon nanowires could be enhanced 3.8 times under a tensile strain 3.4 %, and could be linearly and reversibly increased 2.7 times under a bending strain up to 14.7 %. In addition, transistors and vacuum tubes of single walled carbon nanotubes with the diameter ~1 nm have been successfully fabricated, with the chirality dependent transport properties demonstrated. Furthermore, deformation of atomically thin two-dimensional crystals has been studied, revealing the ultimately high flexibility, paving the way for the high performance flexible electronic devices.

研究分野： Nanomaterials

キーワード： electron microscopy　nanowire transitors　mechanical properties　electrical properties

１．研究開始当初の背景

The size of Si based metal–oxide–semiconductor field-effect transistor (MOSFET) has scaled down to ~22 nm from ~10 μm following the Moore's law. There are grand challenges at such a small length scale, from the tunneling current leakage, to the distribution control of the few doping atoms, and to the velocity saturation and reduction of mobility, et al. Therefore, it is a great concern and great interest of "More than Moore". The potential candidates for next generation transistors include silicon nanowires, carbon nanotubes, and two-dimensional crystals. It is of great importance to study the fundamental mechanical and electrical properties of such candidate nanostructures, so as to design reliable devices and enhancing the electrical performance by mechanical engineering.

２．研究の目的

The purpose of the project is to fabricate electrical devices of the nanostructures and measuring their electrical properties directly, so that the performance such as the mobility could be directly correlated to the microstructure. Importantly, mechanical stress could be applied so as to study the mechanics and strain effects on the electrical properties. Accordingly, an in situ electron microscopy probing technique was developed.

３．研究の方法

(1) Silicon nanowires were grown by using the chemical vapor deposition (CVD) method using SiH_4 as the precursor and gold nanoparticles as the catalysts. During the growth, desired doping was carried out by introducing PH_3 or B_2H_6 gases.

(2) The nanostructures were dispersed in ethanol and then transferred to a gold wire edge, which acted as the electrode during electrical measurements. And the sample was approached and contacted inside the transmission electron microscope using STM-TEM in situ sample holder, where a piezo-electric motor was used to control the motion of a nanoprobes precisely in three dimensions.

(3) Contacts were made by electron beam assisted welding and then mechanical stress was applied by moving the STM probes. Electrical measurements were carried out during the mechanical tests. Microstructures were finely characterized by the electron microscopy in real time.

４．研究成果

(1) Strain engineering the electron mobility of Si nanowires under tension

As demonstrated in Figure 1, a Si nanowire was loaded between a gold electrode and a STM probe by electron insisted welding. Axial elongation was applied to the nanowire by retracting the probe using the piezo-motor (Figure 1a-d). For the exemplified nanowire, it could sustain up to 3.4 % strain before fracture, much higher than that of the bulk Si crystals. Accordingly, during the tensile test, current-voltage (I-V) curves were measured, shown in Figure 1e. All the curves demonstrated a non-linear relationship revealing that the nanowire is semiconductor and the transport is determined by the contact barriers. With the increase of the tensile strain, the current was increased up to 100 nA for the bias of 4 V. The I-V curves were analyzed by fitting with the PKUMSN program (Figure 1f). And the electrical properties could be calculated. The mobility of the Si nanowire was increased from 2.9 to 11.1 cm^2/(V.s), 3.8 times under the tensile strain of 3.4 %, demonstrating the great potential for strain engineering of the Si nanowire transistors.

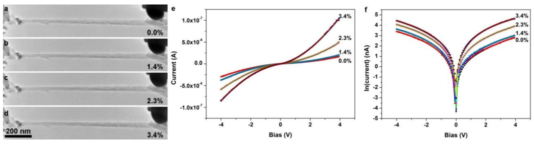

Figure 1 Strain engineering of a Si nanowire under tension. (a-d) Tensile/electrical test of a Si nanowire by in situ TEM method. (e-f) Measured and fitted I-V curves of the nanowire under different tensile strain.

(2) Strain engineering the electron mobility of Si nanowires under bending

Besides the tensile strain, the effects of strain on the electron transport of the Si nanowire under bending were further investigated. For the purpose of bending, the left end was not firmly welded to the electrode and bending was applied by moving the probe (Figure 2a-c). Under bending, the nanowire could sustain much higher strain compared under tensile strain. Accordingly, the I-V curves were recorded and analyzed (Figure 2e-f). It was demonstrated that the current could be modulated two orders of magnitude from a few nano-Amperes to ~ 840 nA under the bias of 4 V. The electron mobility of the nanowire was enhanced from 11.9 to 31.8 cm^2/(V.s).

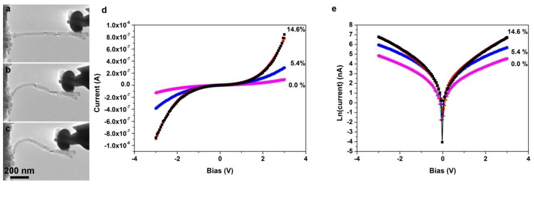

Figure 2 Strain engineering of a Si nanowire under bending. (a-c) Bending/electrical test of the individual Si nanowire. (d-e) Recorded and fitted I-V curves of the Si nanowire under bending.

(3) Fabrication of single walled carbon nanotube transistors and vacuum tubes

In addition to the Si nanowire mechanical/electrical properties, in the current project, the electrical properties of an extreme system: single walled carbon nanotubes with the diameter as small as 1 nm have been investigated. As shown in Figure 3, firstly an in situ biasing technique was applied to shrink a multi-walled carbon nanotube in to a single walled carbon nanotube (Figure 3a-b). The nanotube was clamped between the source and drain electrodes, and a gate voltage could be applied by another gate electrode. The transport properties were measured and demonstrated in Figure 3c-d. When the nanotube is semiconducting, which is determined by the chirality, the nanotube showed a typical ambipolar feature, with the current increase along with the gate voltage.

In addition, the single walled carbon nanotube was engineered into a field emission tip by electron beam and current annealing (Figure 4). In contrast to the ambipolar transistor characteristics, the SWCNT vacuum triode demonstrated that the circuit is open when the gate voltage is positive, revealing that in this case the charge carrier is the negative charge, electrons. In both the transistors and the vacuum triode, the 1 nm SWCNT demonstrated modulating ON/OFF ratio larger than 10^3. Because of the absence of substrate scattering, these electrical devices are promising for future high mobility applications.

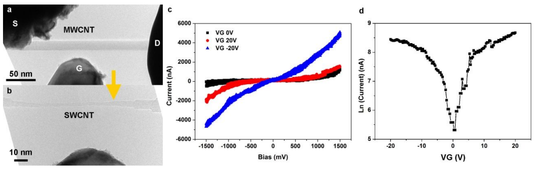

Figure 3 SWCNT transistor. (a-b) Fabrication of a SWCNT transistor. (c) I-V curves recorded at different gate voltage. (d) Current recorded with the gate voltage swiping from -20 V to 20 V.

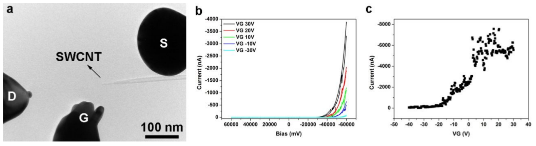

Figure 4 SWCNT vacuum tube triode. (a-b)

Fabrication of a SWCNT vacuum tube triode. (c) I-V curves recorded at different gate voltage. (d) Current recorded with the gate voltage swiping from -40 V to 40 V.

(4) Ultimate flexibility of the two-dimensional molybdenum disulphide crystals

In the current project, in addition to the one-dimensional nanowire/nanotubes, the mechanical properties of a two-dimensional system were investigated, with the purpose of evaluating their properties for the flexible electronics. As shown in Figure 5, the mechanical cleavage processes and associated mechanical behaviors are investigated by a direct in situ TEM probing technique, using atomically-thin molybdenum disulphide layers as a model material. Our technique demonstrates layer number selective cleavage, from a monolayer to double layer and up to 23 atomic layers. In situ observations combined with molecular dynamics simulations reveals unique layer-dependent bending behaviors: from spontaneous rippling (< 5 atomic layers) to homogeneous curving (~ 10 layers), and finally to kinking (20 or more layers), depending on the competition of strain energy and interfacial energy.

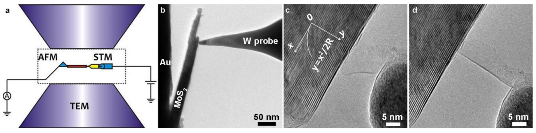

Figure 5 Manipulation and flexibility test of the atomically thin 2D crystals. (a-b) Schematic and TEM image of the in situ TEM probing method. (c-d) Snapshots of the atomically thin crystal under bending and tension, respectively.

５．主な発表論文等

（研究代表者、研究分担者及び連携研究者には下線）

〔雑誌論文〕（計　6　件）

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〔図書〕（計　0　件）

〔産業財産権〕

○出願状況（計　0　件）

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権利者：
種類：
番号：
出願年月日：
国内外の別：

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名称：
発明者：
権利者：
種類：
番号：
取得年月日：
国内外の別：

〔その他〕

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