TOYOHASHI UNIVERSITY of TECHNOLOGY
Hibarigaoka, Tempaku, Toyohashi, Aichi, 441-8580 Japan
PHONE: +81-532-44-6577 FAX: +81-532-44-6557
E-mail: press@office.tut.ac.jp

PRESS RELEASE

Source: Toyohashi University of Technology, Japan, Committee for Public Relations

Title: Unveiling the electron's motion in a carbon nanocoil
Subtitle: Development of a precise resistivity measurement system for quasi-one-dimensional nanomaterials using a focused ion beam

Full text:
Carbon nanocoils (CNCs) are an exotic class of low-dimensional nanocarbons whose helical shape may make them suitable for applications such as microwave absorbers and various mechanical components such as springs. Typical thicknesses and coil diameters of CNCs fall within the ranges of 100–400 nm and 400–1000 nm, respectively, and their full lengths are much larger, on the order of several tens of micrometers. Despite earlier pioneering work, the relationships between the geometric shape of natural CNCs and their mechanical and electrical properties, particularly the electrical resistivity, are not well understood.

Now, researchers at Toyohashi Tech, University of Yamanashi, National Institute of Technology, Gifu College, and Tokai Carbon Co., Ltd. have established that the resistivity of CNCs increases with coil diameter. This required the development of a precise resistivity measurement method, using a focused ion beam (FIB) and nanomanipulator technique to select a sample CNC with the desired coil geometry and then make firm electrical connections to the instrument’s electrodes. All the resistivity data obtained with CNCs were well fitted by a curve predicted by a theory known as variable range-hopping (VRH), which is suitable for disordered materials at low temperatures.

The research shows that the interior of the nanocoil contains material that affects its electrical properties. The scientists examined 15 individual CNCs, and three CNCs that had been artificially-graphitized to give them lower resistivity (G-CNCs). Although the resistivity of the CNCs increased with coil diameter, it was almost unchanged for the G-CNCs. As a consequence, for the CNCs with the largest diameters, the resistivity was almost two orders of magnitude larger than that of the graphitized versions. This large discrepancy in the resistivity between CNCs and G-CNCs indicates a significant structural complexity inside the CNCs. Our results imply that the interior of CNCs with large coil diameter is filled with a highly-disordered carbon network that consists of many small regions (known as sp2 domains) embedded in a sea of amorphous carbon. To verify this theory, the temperature dependence of the resistivity between 4 K and 280 K was examined. The resistivity data obeyed two different versions of the VRH theory; the regime in the temperature range of 50–280 K was found to be the so-called Mott-VRH version, while that in the range of 4–20 K was the Efros–Shklovskii-VRH version. Interestingly, the resistivity curves shifted smoothly between regimes as the coil diameter was changed.

TOYOHASHI UNIVERSITY of TECHNOLOGY
Hibarigaoka, Tempaku, Toyohashi, Aichi, 441-8580 Japan
PHONE: +81-532-44-6577 FAX: +81-532-44-6557
E-mail: press@office.tut.ac.jp

"We found this behavior three years ago. Owing to the efforts of two students, we included the resistivity data for G-CNCs and straight carbon nanofibers (CNFs), and compared them to the data for the CNCs", explains Associate Professor Yoshiyuki Suda, "I am so glad that Prof. Hiroyuki Shima and Dr. Tamio Iida joined this study. We obtained the low-temperature measurement data and discussed it using the VRH theory. Eventually, we came to the conclusion that this behavior is a unique phenomenon for CNCs and can be fitted by VRH."

The first author, Master's course student Yasushi Nakamura, commented on how they went beyond the CNC resistivity measurements of other groups. "It was a long and challenging task. I had to prepare many single CNC samples using a focused ion-beam apparatus. Our finding was achieved by establishing a precise measurement system using a scanning electron microscope and acquiring resistivity data for many single CNCs."

The group's present results on resistivity are in qualitative agreement with their previous findings on the mechanical properties of CNCs: Tensile load experiments showed that their shear modulus increases with coil diameter. The positive correlation between the shear modulus and coil diameter is possibly caused by the fact that in large-diameter CNCs, the population of sp2 domains, which are fragile against shear stress, is reduced in comparison to small-diameter CNCs.

These results imply that, with nanocoils, the resistance as well as the inductance are defined by geometric factors. In particular, coil diameter, pitch, and length are important. The correlation found can be used to improve control over the peak frequency of electromagnetic wave absorption, in which a particular range of frequencies (~GHz) is absorbed, dependent on the impedance properties.

These findings pave the way for CNC-based nanodevices, ranging from electromagnetic wave absorbers to nano-solenoids and extra-sensitive mechanical springs.

Funding agency: This work was partly supported by JSPS KAKENHI Grant Numbers 24360108, 25390147, and 15K13946, and the Toyota Physical and Chemical Research Institute.

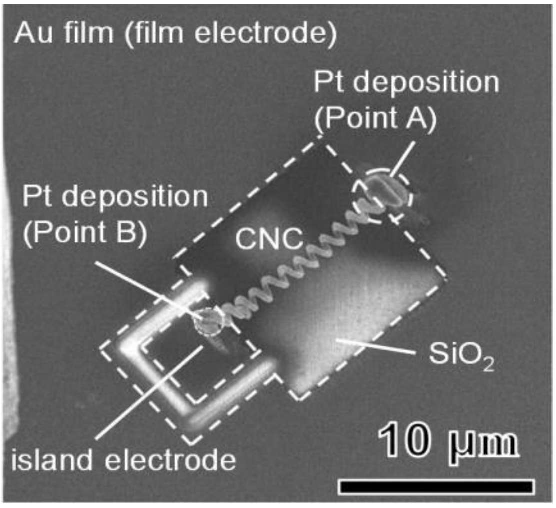
Reference:
Yasushi Nakamura, Yoshiyuki Suda, Ryuji Kunimoto, Tamio Iida, Hirofumi Takikawa, Hitoshi Ue, and Hiroyuki Shima (2016). Precise measurement of single carbon nanocoils using focused ion beam technique, Applied Physics Letters, 108, 153108. 10.1063/1.4945724

TOYOHASHI UNIVERSITY of TECHNOLOGY
Hibarigaoka, Tempaku, Toyohashi, Aichi, 441-8580 Japan
PHONE: +81-532-44-6577 FAX: +81-532-44-6557
E-mail: press@office.tut.ac.jp

Further information
Toyohashi University of Technology
1-1 Hibarigaoka, Tempaku, Toyohashi, Aichi Prefecture, 441-8580, JAPAN
Inquiries: Committee for Public Relations
E-mail: press@office.tut.ac.jp

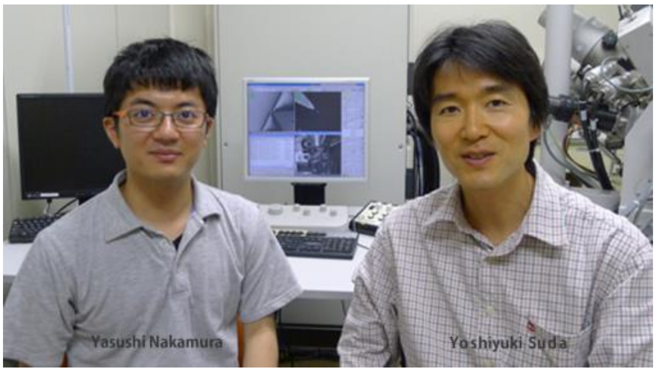
Toyohashi University of Technology founded in 1976 as a National University of Japan is a research institute in the fields of mechanical engineering, advanced electronics, information sciences, life sciences, and architecture.
Website: http://www.tut.ac.jp/english/

Figure 1:



Caption: Scanning electron microscope image of the resistivity-measuring electrical circuit, in which a single carbon nanocoil makes excellent contact with the electrodes.

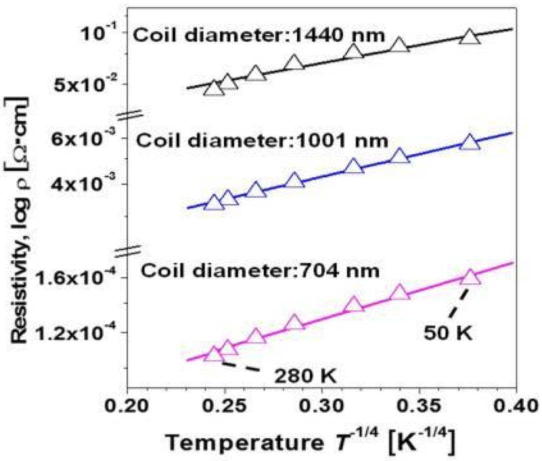
Figure 2:



Caption: Master’s course student (graduated in March 2016) Yasushi Nakamura (left) and Associate Professor Yoshiyuki Suda (right).

TOYOHASHI UNIVERSITY of TECHNOLOGY
Hibarigaoka, Tempaku, Toyohashi, Aichi, 441-8580 Japan
PHONE: +81-532-44-6577 FAX: +81-532-44-6557
E-mail: press@office.tut.ac.jp

Figure 3:



Caption: Dependence of the resistivity of carbon nanocoils on temperature, for different coil diameters. The graph's axes, log resistivity (ρ) and T–1/4, are used to simplify the portrayal of the functional dependence. Solid lines in this figure show the best fit to the data with the Mott-VRH model.

Keywords: CHEMISTRY/PHYSICS/MATERIALS SCIENCES, ELECTRICAL ENGINEERING/ELECTRONICS, ELECTROMAGNETICS, ELECTROMAGNETICS, ENERGY/FUEL (NON-PETROLEUM), MATERIALS, NANOTECHNOLOGY/MICROMACHINES, NANOTECHNOLOGY/MICROMACHINES, RESEARCH/DEVELOPMENT, TECHNOLOGY/ENGINEERING/COMPUTER SCIENCE