# Japan Academy Prize to:

Kunio Takayanagi Professor and Professor Emeritus, Tokyo Institute of Technology

for "Investigation of Nano-structures using an Ultra-high Vacuum Electron Microscope"



# Outline of the work:

### 1. Investigation of the atomic structure of the 7x7 reconstructed Si (111) surface

The atomic structure of Si (111) surface was supposed to be constructed from a triangular lattice. Actually, that surface has a period 7 times larger than that of the unit cell. Since the discovery of the Si (111) 7x7 structure in 1959, the arrangement and combination of its atoms had not been clarified for more than 20 years.

The main technique for surface structure determination is low-energy electron diffraction. However, the interaction between the low-energy electron and the atoms on the surface is strong, making analysis of the data difficult. Many surface scientists have tackled this problem but no definite results have been obtained.

Prof. Kunio Takayanagi and his group used the transmission electron diffraction (TED) method. As the electron energy of TED is high and interaction between the electron and the atoms on the surface is weak, analysis is made easier. His group proposed the DAS model. This model involves 15 dimers and 12 adatoms in the unit cell with half of the atoms in the second layer shifting horizontally, a stacking fault results. DAS comprises the initial characters of these technical terms.

The merit of this reconstruction of atoms, superior to the triangle lattice, lies in its decreased number of dangling bonds. The original Si (111) surface has 49 dangling bonds per unit cell. In contrast, the DAS model has only 19 dangling bonds, resulting in system stability.

Later experiments such as on surface X-ray diffraction and low-energy electron diffraction and first principle calculations confirmed the validity of the DAS model, which thereafter became widely recognized as the ultimate model of Si 7x7 reconstruction.

#### 2. Conductivity measurement of quantum nano-wires of gold

Prof. Takayanagi used gold to make a chip for a scanning tunneling microscope; he touched the chip to a gold sample and then pulled them apart. A gold nano-wire was formed between the chip and the gold sample. He inserted this system into a ultra-high-vacuum electron microscope. While observing the nano-wire, he measured the electrical conductivity between the chip and the sample. He found the conductivity to be  $2e^2/h$  when the nano-wire consists of a single gold wire and to be twice  $2e^2/h$  when the nano-wire consists of double gold wires. (e: electron charge, h: Planck constant) This was the first time for the conductivity of a nano-wire to be measured while observing the nano-wire.

#### 3. Discovery of a nano-tube of gold

Prof. Takayanagi radiated a gold thin film in an ultra-high-vacuum electron microscope and made holes of the film. Further radiation caused two holes to stick together. He found that the stuck part forms a nano-tube with a multi-layer structure. One layer consists of a spiral tube consisting of several atomic chains. The number of chains in each layer is denoted as n-n'-n". Then, the observed chains were 7-1, 11-4, 12-5, 13-6, 14-7-1, 15-8-1, 16-9-2. The number of atomic

chains has a distinctive feature and saturate when n-n'=7, and one more layer is formed when the number of chains increases. So, 7 is a magic number.

Carbon nano-tubes were well known, but Prof. Takayanagi demonstrated that nano-tubes can even be made from gold.

## 4. Domestic development of sub-50pm resolution electron microscope

Spherical aberration correction technique for electron microscopes had been a practical technique in Europe and United States during the period 1995~1999, with resolution becoming as high as 100 pm. Japan fell behind in this technique. Then, Prof. Takayanagi developed an original aberration correction technique obtaining sub-50 pm resolution, allowing Japan to again spearhead microscope technique and nano-structure observation.

## **References:**

- 1. K. Takayanagi, D. M. Kolb, G. Lehmphul and K. Kambe: Surface Science, 100, 1981 (1980).
- 2. K. Takayanagi: Surface Science, 104, 527 (1981).
- 3. K. Takayanagi: Journal of Microscopy, 136, 287 (1982).
- 4. K. Takayanagi, Y. Tanishiro, S. Takahashi and M. Takahashi: Surface Science, 164, 367 (1985).
- 5. J. J. Metois, K. Takayanagi, Y. Tanishiro and K. Yagi: Surface Science, 155, 53 (1985).
- 6. T. Nakayama, Y. Tanishiro and K. Takayanagi: Jpn. J. Appl. Phys., 26, L1186 (1987).
- 7. K. Yamazaki, Y. Tanishiro, K. Takayanagi and K. Yagi: Surface Science, 199, 595 (1988).
- 8. T. Yokoyama and K. Takayanagi: Phys. Rev. B57, R4226 (1998).
- 9. T. Yokoyama, M. Okamoto and K. Takayanagi: Phys. Rev. Lett., 81, 3424 (1998).
- 10. H. Ohnishi, Y. Kondo and K. Takayanagi: Nature, 395(6704), 780 (1998).
- 11. Y. Kondo, Q. Ru and K. Takayanagi: Phys. Rev. Lett., 82, 751(1998).
- 12. Y. Kondo and K. Takayanagi: Science, 289, 606 (2000).
- 13. Y. Ohshima, H. Koizumi, Y. Kondo, K. Mouri, H. Hirayama and K. Takayanagi: Phys. Rev. B65, 121401(R) (2002).
- 14. Y. Ohshima, A. Onga and K. Takayanagi: Phys. Rev. Lett., 91, 205503 (2003).
- 15. M. Yoshida, Y. Ohshima and K. Takayanagi: Appl. Phys. Lett., 87, 103104 (2005).
- 16. Y. Kurui, Y. Ohshima and K. Takayanagi: Phys. Rev. B77, 161403R (2008).
- 17. Y. Kurui, Y. Ohshima and K. Takayanagi: Phys. Rev. B79, 165414 (2009).
- S. Lee, Y. Oshima, H. Sawada, F. Hosokawa, E. Okunishi, T. Kaneyama, Y. Kondo, S. Niitaka, H. Takagi, Y. Tanishiro and K. Takayanagi: J. Applied Physics, 109, 113530 (2011).
- 19. Y. Ohshima, Y. Kurui, H. D. Nguyen, T. Ono and K. Takayanagi: Phys. Rev. B84, 035401 (2011).
- 20. Y. Ohshima, Y. Kurui and K. Takayanagi: Applied Physics Express, 4, 055002 (2011).