Curriculum Vitae

Yahachi Saito

[Title]
Emeritus Professor, Nagoya University

[Research Field]
Materials Science, Crystal Physics, Nanoscience

[Date of Birth]
Feb. 28, 1953

[Education]

March 1975 Bachelor of Engineering, Nagoya University
March 1977 Master of Engineering, Nagoya University
March 1980 Doctor of Engineering, Nagoya University

[Professional Career]

April 1980 Research Scholar, Japan Society for the Promotion of Science
January 1981 Assistant Professor, Toyohashi University of Technology
(Oct. 1984 - Dec. 1984 and July 1985 - Sept. 1985; Visiting Scientist, AT&T Bell Laboratories)
November 1985 Assistant Professor, Faculty of Engineering, Nagoya University
February, 1990 Associate Professor, Faculty of Engineering, Mie University
April 2000 Professor, Mie University
April 2004 Professor, Nagoya University
April 2018 - present Fellow, Toyota Physical and Chemical Research Institute

[Membership in Academic Circles]

Physical Society of Japan, The Japan Society of Applied Physics, The Japanese Society of Microscopy, The Japan Society of Vacuum and Surface, The Fullerenes, Nanotubes and Graphene Research Society

Research Overview

Yahachi Saito

The author's research field is solid state physics for nanoscale materials, especially, studies on the formation and physical properties of nanoscale materials such as atomic cluster, ultrafine particles, carbon nanotube (CNT) and graphene. From 1975 to 1996, starting his research work on the growth and crystallography of ultrafine particles, generation of an atomic cluster beam and its mass analysis, he shifted his research interests to the production and characterization of C_{60} fullerene, CNT and related substances. Since 1996, he focuses on field emission from nanocarbon and its application to electron sources.

1. Growth and structure of ultrafine particles and atomic clusters (1975-1991)

Ultrafine particles of various elements were prepared by a method of evaporating a raw material in an inert gas to obtain fine particles (particle size in a range from ca. 5 to 100 nm), so-called "gas evaporation method" (Fig. 1), and crystallographic studies of the prepared particles by electron microscopy were carried out to reveal crystal structures, morphology and growth mechanism. Major achievements include the discovery of a new crystal structure of Ge (tetragonal system), the formation of Mo and W ultrafine particles with the A-15 type structure, and the creation of quasicrystal ultrafine particles with five-fold rotational symmetry.

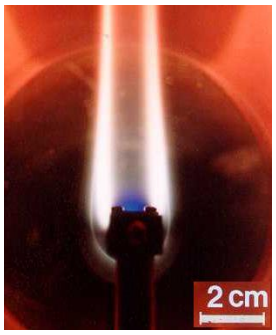

Fig. 1. Smoke of fine Cu particles.

In the study of atomic cluster beam generation and mass spectrometry, using a home-made atomic cluster generator comprised of a supersonic nozzle beam and a time of flight (TOF) mass spectrometer, size distribution of metal atom clusters (Fig. 2) and size-dependent ionization potentials were investigated. This is the first in Japan to measure the physical properties of metal atom clusters using

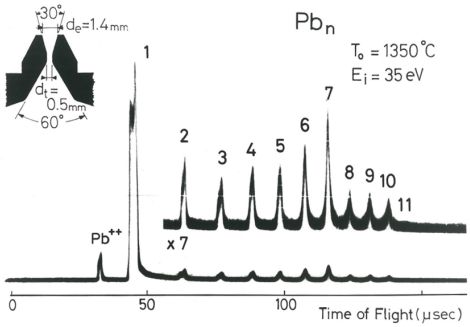

Fig. 2. TOF mass spectrum of Pb clusters formed by supersonic nozzle expansion.

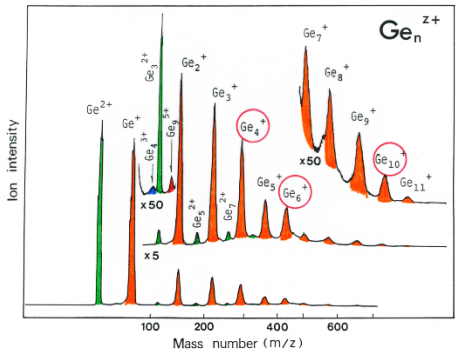

Fig. 3. Mass spectrum of Ge clusters generated by LMIS.

a beam in vacuum. In addition to this nozzle beam method, a liquid metal ion source (LMIS) was employed to generate various atomic clusters such as Li, Na, Au, Si, Ge, and Sn (Fig. 3). Size distributions of clusters, “magic” numbers (the number of constituent atoms forming stable clusters), and the size-dependent stability and so on were studied by mass spectrometry.

2. Synthesis and characterization of C_{60}, CNT and related substances (1990 - present)

Synthesis of C_{60} and other fullerenes was carried out at the earliest time in Japan, and the growth and crystal structures of fullerenes aggregates and thin films were studied. As a substance related to fullerenes, we discovered graphitic cages containing metal ultrafine particles named carbon nanocapsules (Fig. 4). This discovery was introduced in Nature magazine as an exploration toward a new research field of the substance trapped in nanometer space (Nature **361**, 297 (1993)). The synthesis research of carbon nanocapsules containing metal fine particles had been a clue to the discovery of single-walled carbon nanotubes (SWCNTs) growing from metal catalysts (Fig. 5).

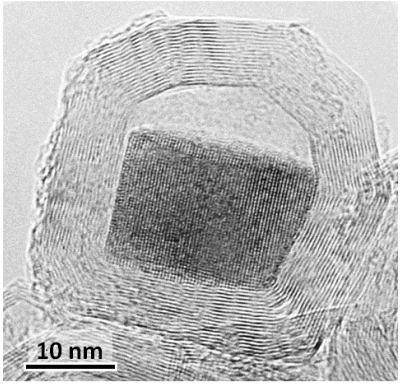

Fig. 4. TEM picture of a carbon nanocapsule containing a LaC_2 crystallite.

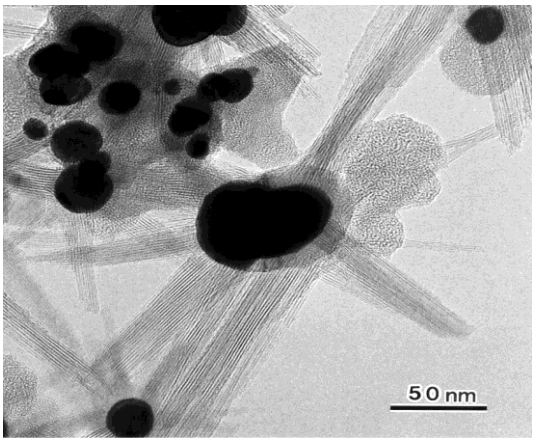

Fig. 5. TEM picture of SWCNT extending from metal catalyst.

3. Field electron emission from CNT and its application to display devices (1996 - present)

In the research on CNT electron emitters, structures of CNT tips were studied for the first time by field emission microscopy (FEM). The result was reported in 1997 (Nature **398**, 554), and gave an impact on the study of the field emission mechanism from nanotubes and its application to new electron sources. As one of applications of CNT field emission electron sources, we succeeded in fabricating a prototype of light emitting devices (Fig. 6) in collaboration with Noritake Ise

Fig. 6. Vacuum fluorescence display (VFD) with CNT cold emitter.

Fig. 7. Character display panel with CNT cathode.

Electronics in 1998. Furthermore, we worked under cooperation between industry and academia to push forward this technology to develop field emission display (FED) and character display panels (Fig. 7).

Unfortunately, the development of the CNT based FED has been discontinued due to the price lowering of the existing flat panel displays and the economic recession caused by the Lehman shock in 2008. But, there are still various applications of CNT electron sources that make use of its unique features. Among them, we focused on development of a compact high-performance field emission scanning microscope (FE-SEM) and an X-ray microscope equipped with a CNT electron source (Fig. 8).

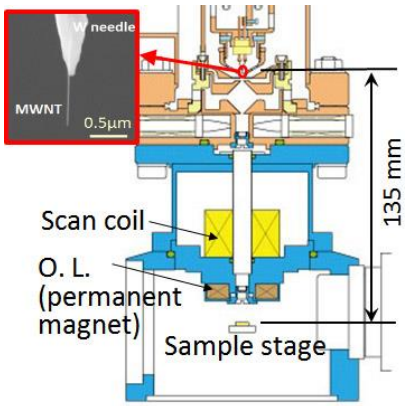

Fig. 8. Desktop FE-SEM equipped with a CNT electron source.

4. Field emission microscopy of CNT and graphene: Observation of carbon pentagons, edge states, and adsorbed molecules (2007 - present)

In addition to research toward practical application of CNT electron sources, we pursued studes on field emission from a fundamental view point, and executed observation of the five-membered rings at the CNT tip and interference of electron waves (see Fig. 9) emitted from adjacent carbon pentagons. Furthermore, we indicated a possibility of atomic resolution observation of molecules (Fig. 10) and Al atom clusters (Fig. 11) on CNT tips.

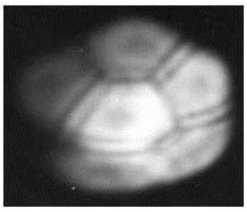

Fig. 9. FEM image of a CNT tip.

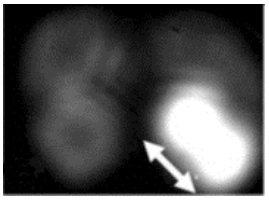

Fig. 10 FEM image of a N_2 molecule on CNT.

Regarding electron emission from graphene, using FEM and transmission electron microscopy (TEM), we have revealed a unique striped FEM image (Fig. 12) that we call a “lip pattern”. The FEM image is characterized by (1) an array of streaked spots extending in the direction perpendicular to the graphene plane, (2) a dark band running through the whole pattern dividing the streaks into two wings, (3) a mirror symmetry with respect to the central dark band. These features can all be explained by the symmetry of the π-electron orbital at a graphene edge. For example, the dark band at the center of the FEM image is due to destructive interference of electron waves emitted from two lobes of a π-electron orbital extending to the upper and lower surface of a graphene with their phase being shifted by π each other, and the bright streaks directed perpendicular to the graphene plane

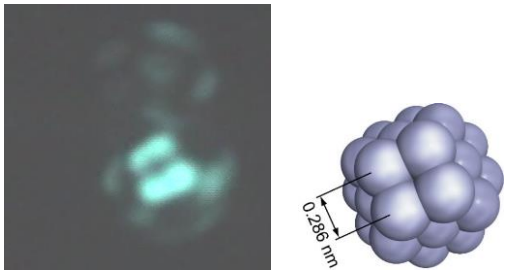

Fig. 11 FEM image of an Al cluster (left) and a structure model of the cluster (right).

represent the π-electrons localized at edge atoms. At the graphene edge (especially at the zigzag edge), electron spins are expected to be ferromagnetically ordered. Under high electric field, electrons at the edge state can be emitted via tunneling effect into a vacuum, so the spin polarization is expected to be directly measured, which would verify the theoretically predicted order state of spins.

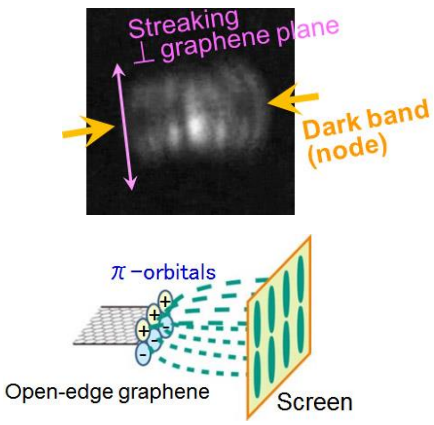

Fig. 12. FEM image of a graphene edge (upper panel) and schematic illustrating its origin (lower).

5. Physical properties of CNT studied by *in situ* transmission electron microscopy (2003-2018)

Electro-migration of copper (Cu) encapsulated inside a CNT, which is bridged between electrodes was studied by transmission electron microscopy (TEM). When an electric current of 10 μA (current density ~10^8 A/cm^2) was passed through a CNT, Cu inside the CNT moved to the electrode side (in a solid state), but the outer CNT was intact, keeping its bridge structure (Fig. 13). This reveals a high durability of CNTs against electro-migration, suggesting that CNT is the most likely candidate to be the next generation inter-connect (wiring) materials in large-scale integrated (LSI) circuits as a successor for Cu, which has reached its limit as the wiring material.

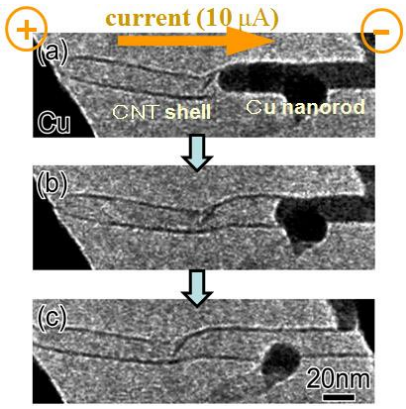

Fig. 13. Electromigration of Cu inside CNT.

In the application of CNT to electronic devices, e.g., channel materials in field effect transistor (FET) as well as the inter-connect in LSI, electrical contacts to metal electrodes with low electrical resistance and high mechanical reliability are very important issues. We have studied electrical contacts between CNT and several metals (Cu, Au and Ni) by in situ TEM (Fig. 14). Contact resistance depending on tip structure (closed or open) of CNT and metals was clarified.

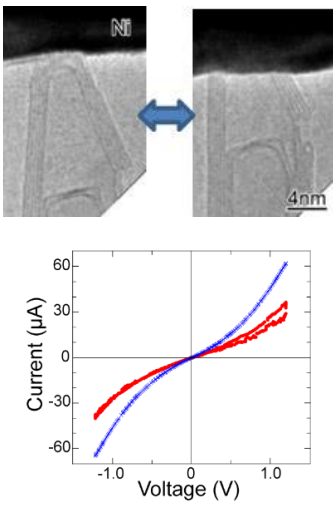

Fig. 14. TEM images of a CNT just touching with and buried (top panel) into Ni electrode, and I-V characteristics (bottom).

Changes in structure and phases of Si nanoparticles deposited on the CNT surface, during a heating process by using the CNT as a heater, were studied by in situ TEM. Structural changes of CNT itself and luminescence from the CNT by Joule heating were

simultaneously observed in TEM. CNT field emitters sometimes set off a violent vibration during FE experiment in TEM as shown in Fig. 15. The auto-vibration of a CNT emitter was investigated under various conditions, e.g., length and diameter of used CNTs, geometrical positioning against an anode, and so on.

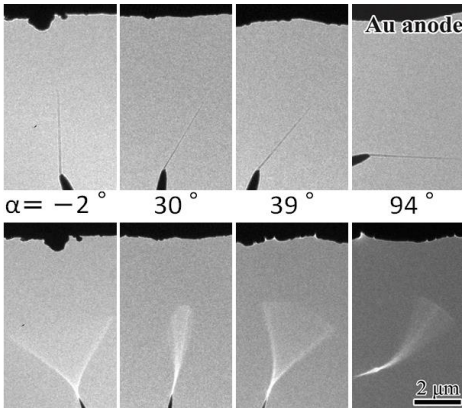

Fig. 15. CNT facing toward an anode at various angles before application of electric voltage (upper panel), and vibrating CNT during FE (bottom).

6. Growth and Structure of Graphene (2007-2018)

Evolution of surface structures of SiC by thermal decomposition and the growth of graphene were investigated by reflection high-energy electron diffraction and ultrahigh vacuum scanning electron microscope/scanning tunneling microscope (UHV-SEM / STM). Graphene nanoribbons were also prepared on the SiC surface by controlling the thermal decomposition process (Fig. 16), and electrical conduction of the nanoribbon was evaluated by 4-probe method.

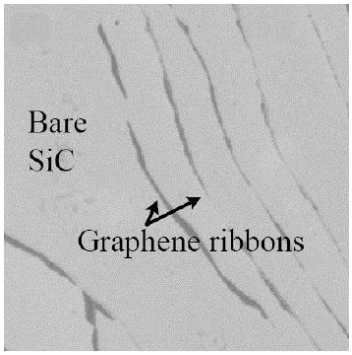

Fig. 16. SEM image of graphene nanoribbons on a SiC surface.

Publication List

Yahachi Saito

Original papers

1) T. Hayashi, Y. Saito, S. Yatsuya, K. Mihama and R. Uyeda: "Morphology of Fine Crystallites Formed by Gas-Evaporation Technique. Face Centred Metals (Al, Co, Ni, Cu, Pd, In, Ag, Au and Pb), Silicon and Germanium", J. de Physique **38** (C2), 191-194 (1977)

2) Y. Saito, S. Yatsuya, K. Mihama and R. Uyeda: "Formation of Ultrafine Particles by Gas-Evaporation Technique. V. Silicon and Germanium in Argon", Jpn. J. Appl. Phys. **17** (2), 291-297 (1978)

3) Y. Saito, S. Yatsuya, K. Mihama and R. Uyeda: "Multiply-Twinned Particles of Germanium ― A Supplement to "Formation of Ultrafine Particles by Gas-Evaporation Technique. V."―", Jpn. J. Appl. Phys. **17** (6), 1149-1150 (1978)

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5) Y. Saito: "Crystal Structure and Habit of Silicon and Germanium Particles Grown in Argon Gas", J. Cryst. Growth **47** (1), 61-72 (1979)

6) Y. Saito, S. Yatsuya, K. Mihama and R. Uyeda: "Formation of Ultrafine Metal Particles by Gas-Evaporation VI. Bcc Metals, Fe, V, Nb, Ta, Cr, Mo and W", Jpn. J. Appl. Phys. **19** (9), 1603-1610 (1980)

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15) M. Watanabe, Y. Saito, S. Nishigaki and T. Noda: "Magic Numbers and Critical Sizes of Tin Clusters Emitted from a Liquid Metal Ion Source", Jpn. J. Appl. Phys. **27** (3), 344-347 (1988)

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