北京大學

Growth of Single-Walled Carbon Nanotubes on Surface with Controlled Structures

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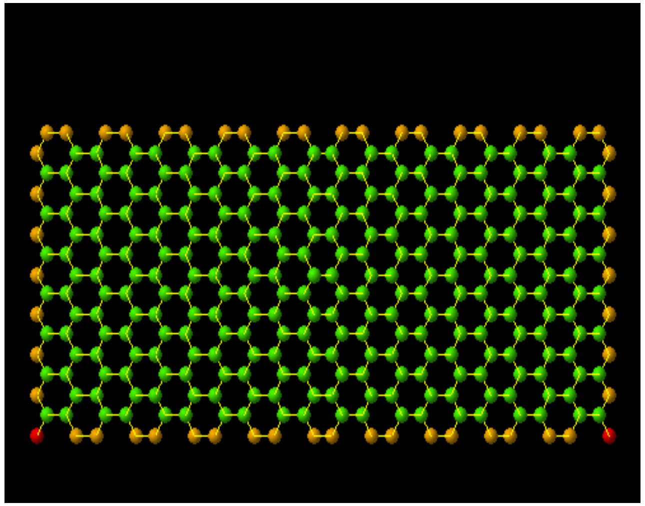
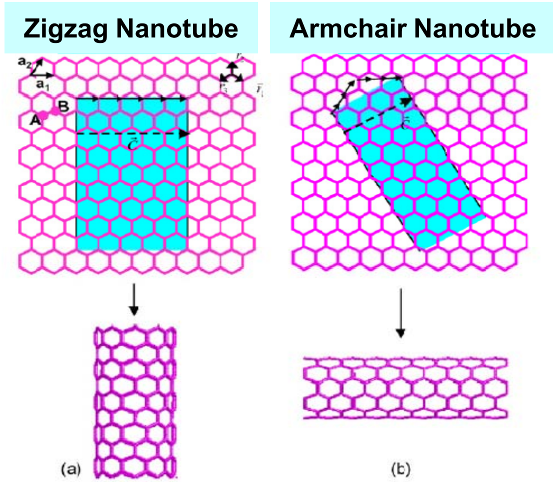
The University of Tokyo, 1st Nov, 2010, Tokyo

Introduction of Single-walled Carbon Nanotubes



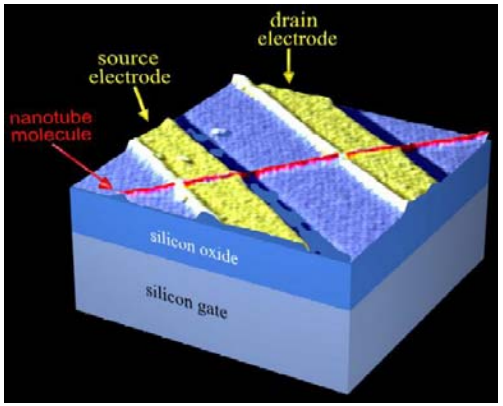


$$C_h = na_1 + ma_2 \equiv (n,m)$$

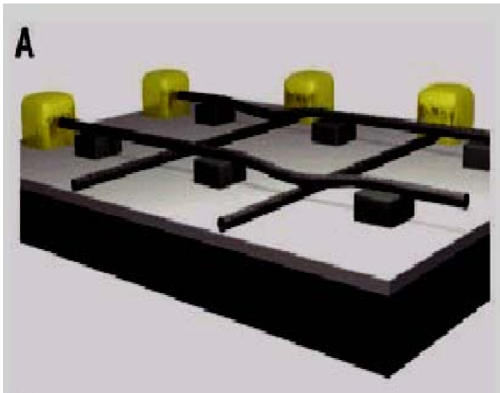
$$d_t = \sqrt{3}a_{C-C}(n^2+m^2+nm)^{1/2}/\pi$$

$$\theta = \tan^{-1}\left(\frac{\sqrt{3}m}{2n+m}\right)$$

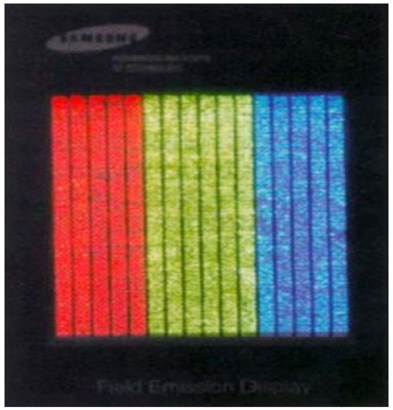
$$n-m = \begin{cases} 3p & \text{metal} \\ 3p\pm 1 & \text{semiconductor} \end{cases}$$



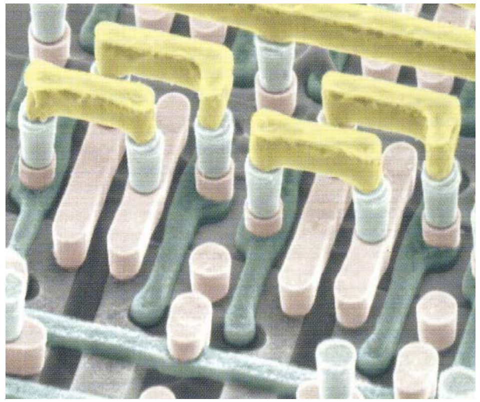
Nanotube transistor



Nanotube RAM

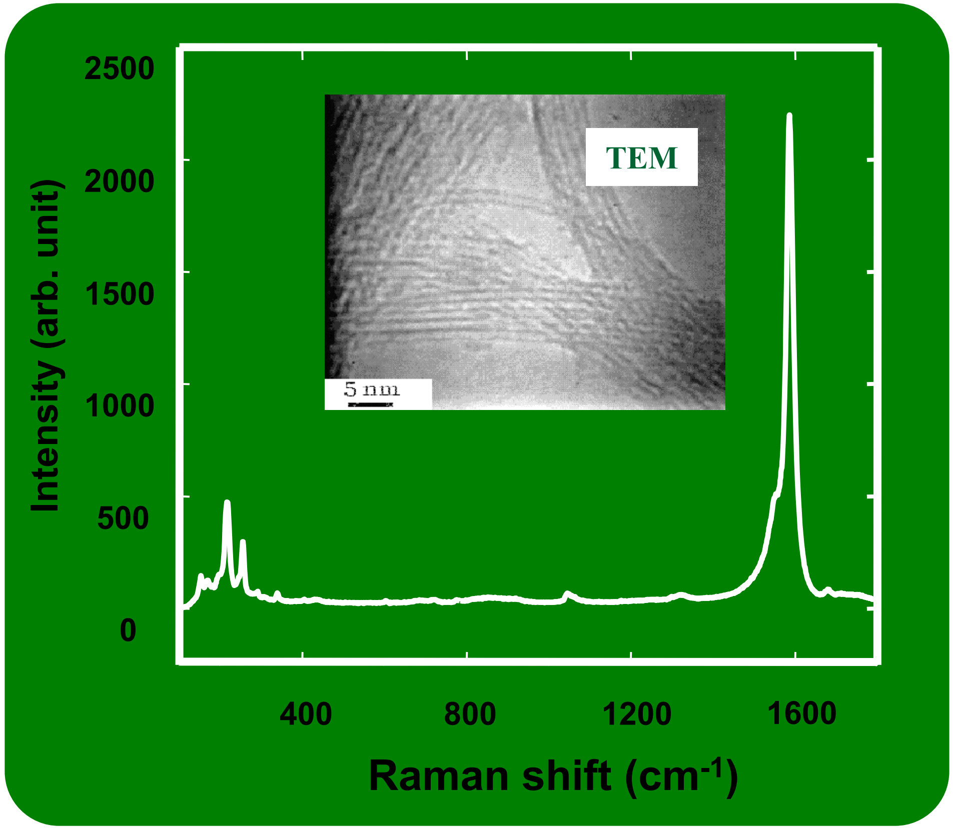


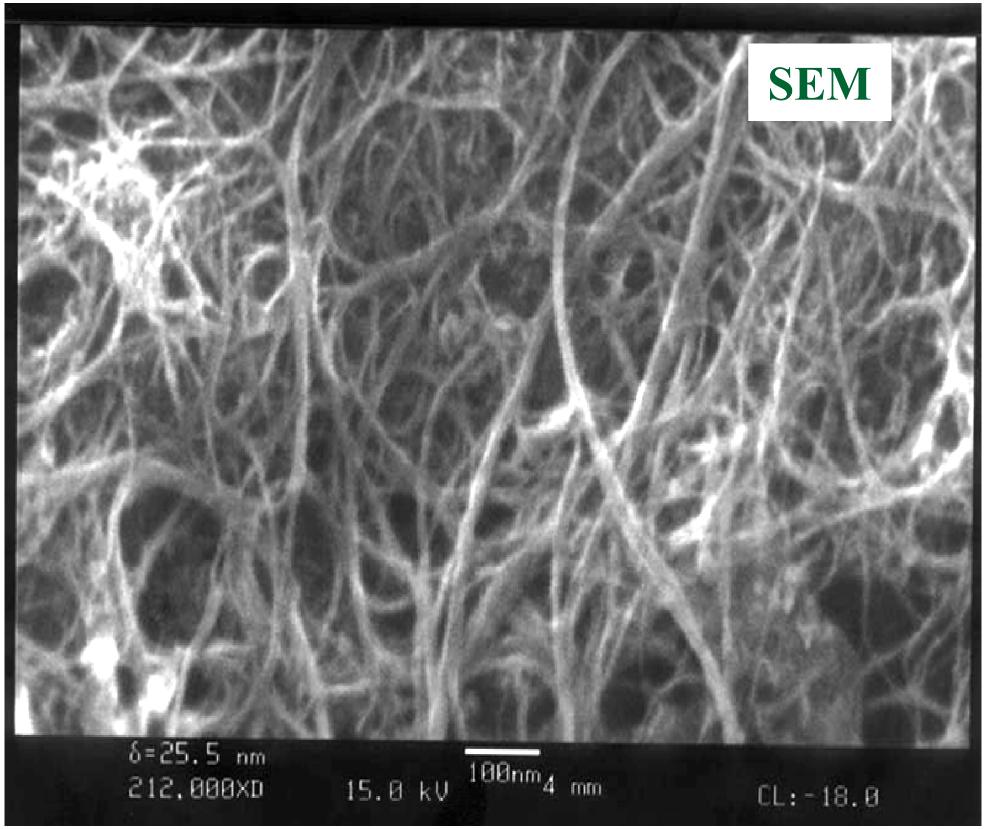
Flat panel display



Nanotube interconnect

A Scalable CVD Synthesis of High-Purity SWNTs with Porous MgO as Support Materials



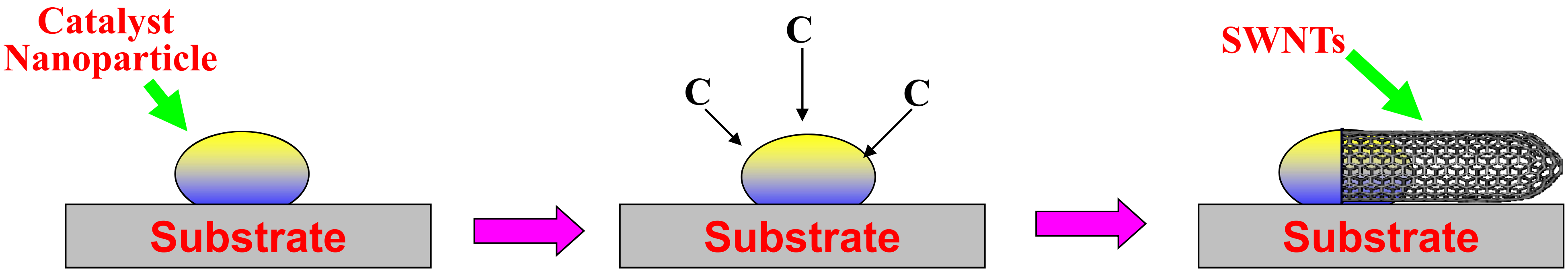


Support: MgO; Catalysts: Fe; Carbon Source: CH_4

J. Zhang et. al. , J Mater Chem, 12(4): 1179-1183, 2002； Carbon, 40(12): 2282-2284, 2002；Carbon, 40(14): 2693-2698, 2002

Surface Growth of SWNTs by CVD

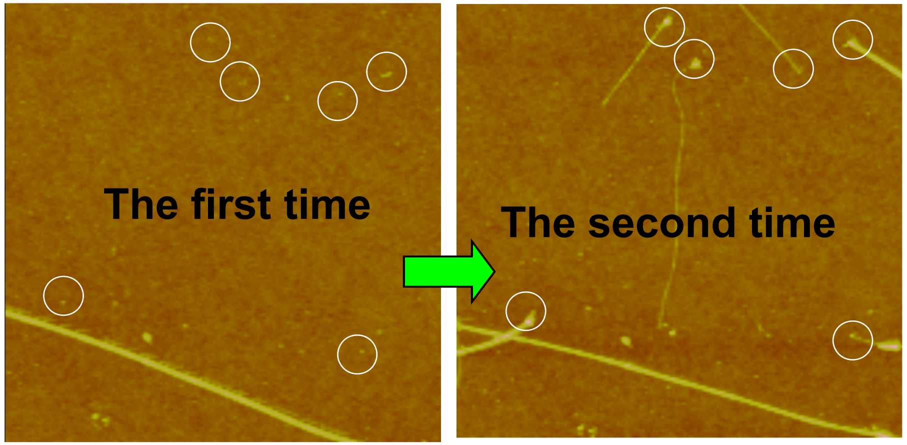
Growth Process:



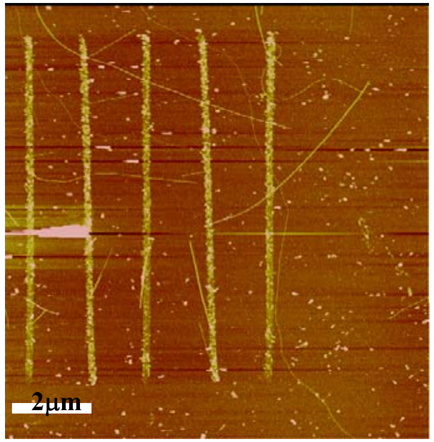
Questions:

1. Growing SWNTs on Surface Directly with Controlled Density, Position and Orientation
2. Growing SWNTs on Surface with Controlled Diameter
3. Growing SWNTs on Surface with Controlled Metallic and Semi-conducting Properties
4. Growing SWNTs on Surface with Controlled Chirality

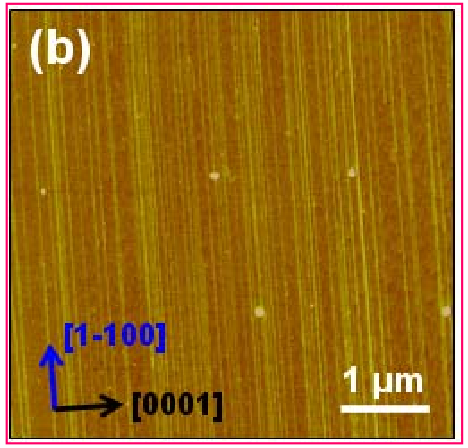
Controlled CVD Growth of SWNTs on Surface



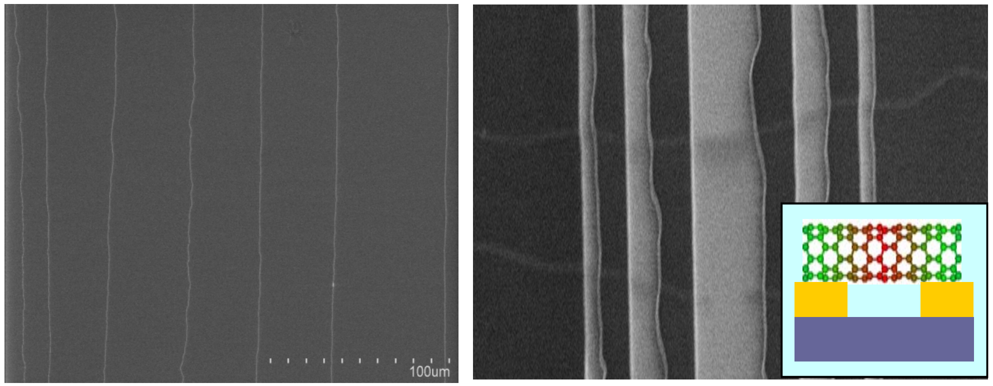
J. Phys. Chem. B. 2004, 108, 12665



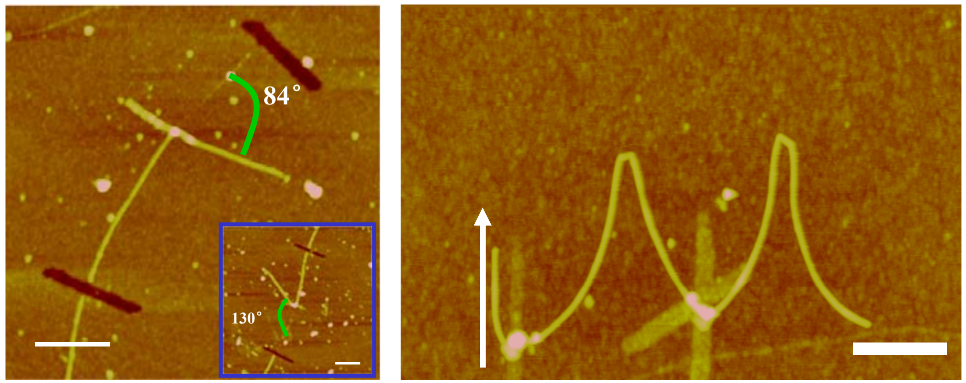
J. Phys. Chem. B, 2005, 109, 10946



J. Phys. Chem. C, 2008, 112, 8319



J. Am. Chem. Soc. 2005,127,17156



J. Am. Chem. Soc. 2005, 127, 8268.
J. Phys. Chem. B, 109 (2005) 2657-2665

Challenges for the Application of Carbon Nanotubes in Future Device

1）How to achieve a structure-controlled synthesis of nanotubes ?

- Diameter
- Lattice geometry (armchair, zigzag, chirality)
- Semiconduting or Metallic Nanotubes

2）How to fabricate a desired device structure ?

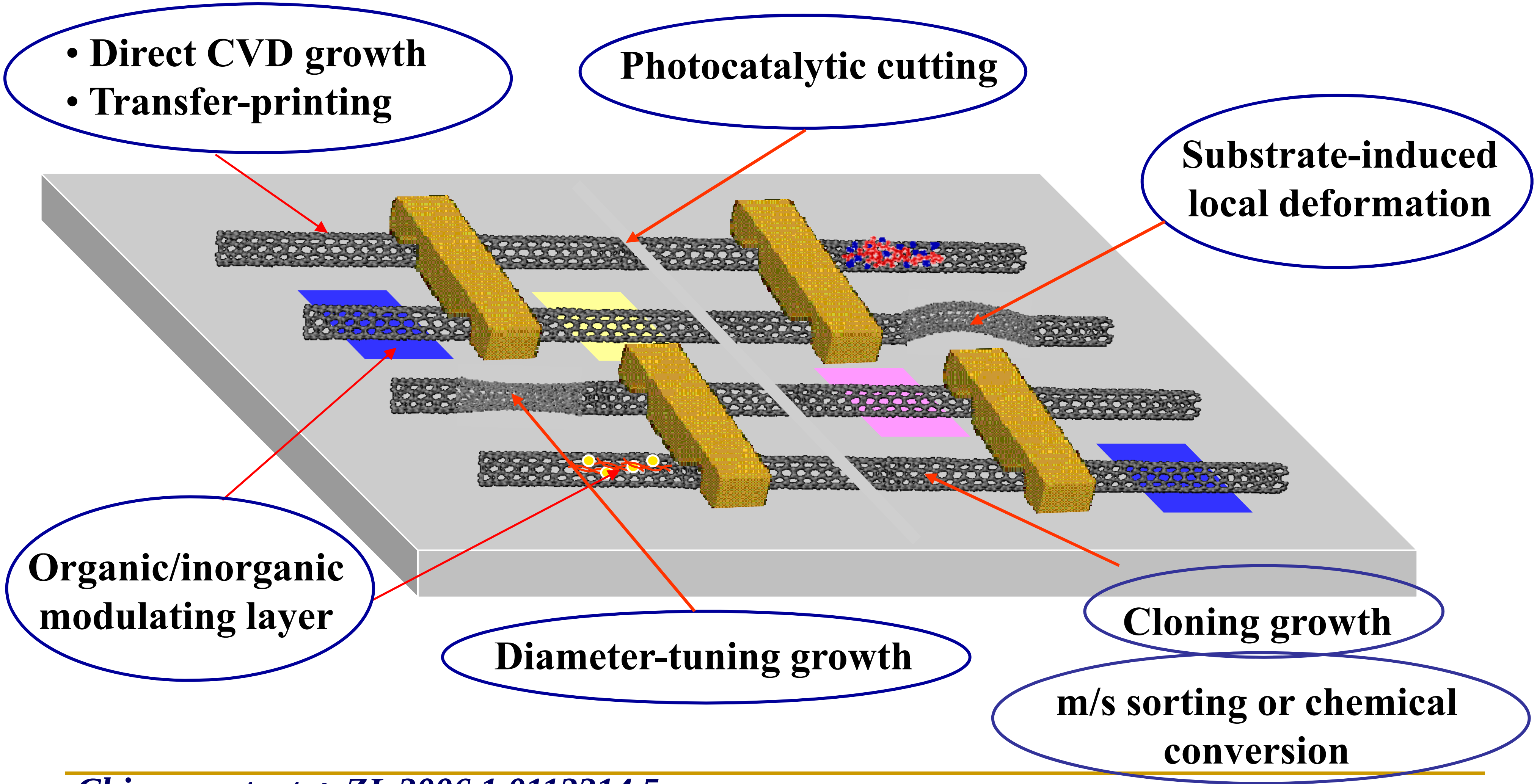
- Controlled surface growth
- Manipulation

3）What architecture should the nanotube device have ?

4）How to integrate trillions of individual nanotube devices ?

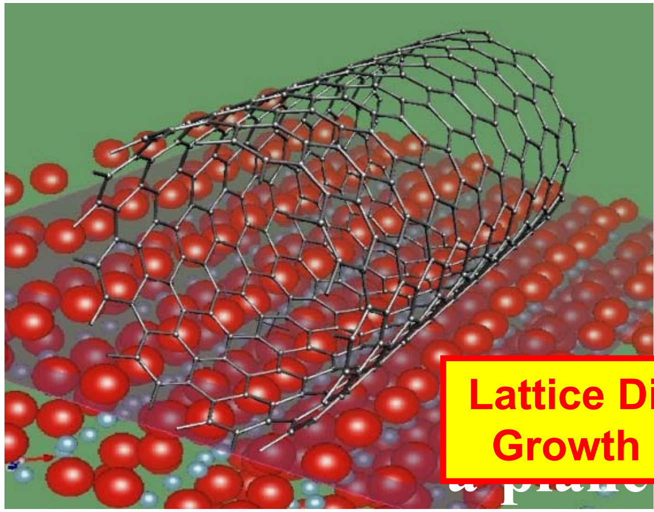
Our strategy towards SWNTs-based CMOS chips

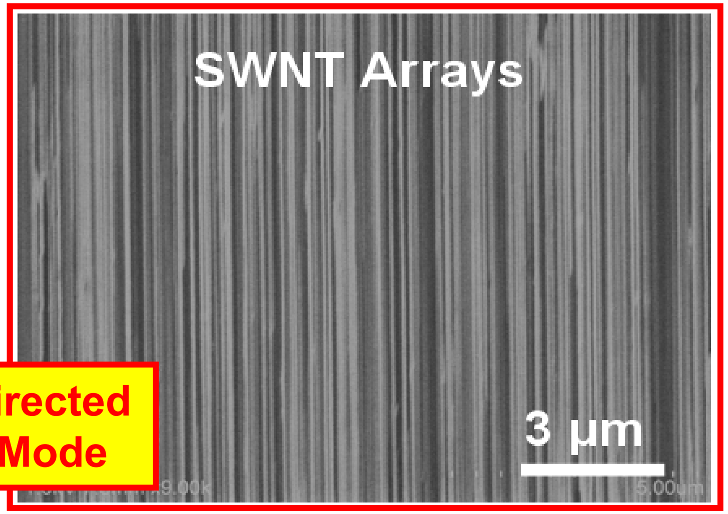
—— Axial Band Structure Engineering

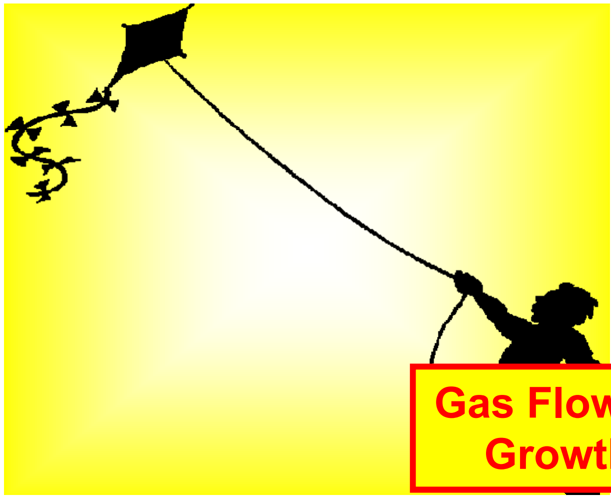


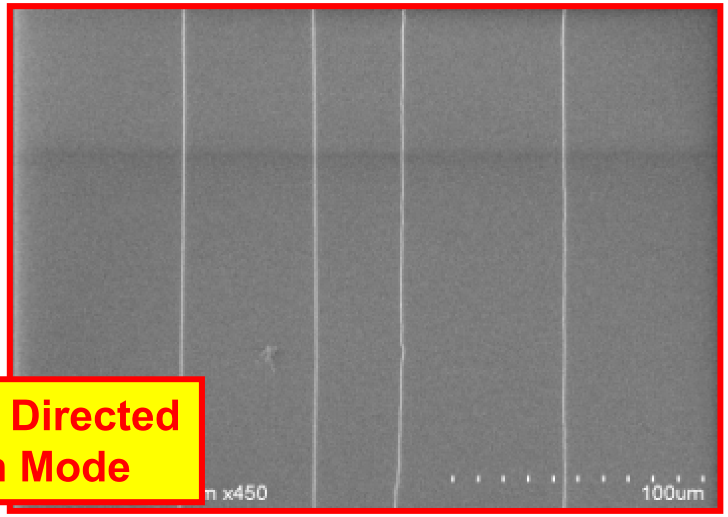
Chinese patent： ZL 2006 1 0113214.5
ZL 2006 1 0113212.6

Catalytic CVD Growth of SWNTs Arrays on Surface





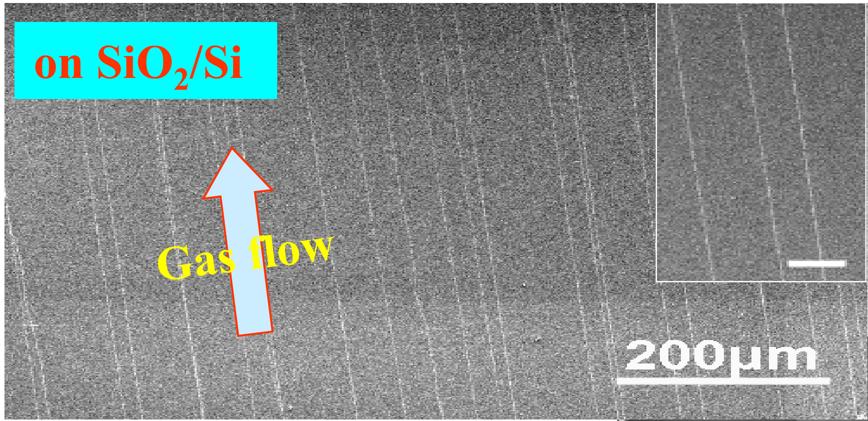




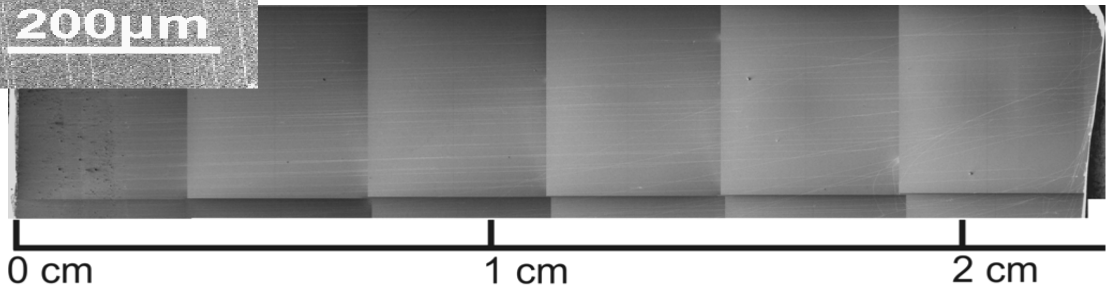
Carbon source : Methane, ethanol, etc
Substrate: Sapphire, quartz, SiO_2/Si, etc

Lattice Directed Growth vs. Gas Flow Directed Growth

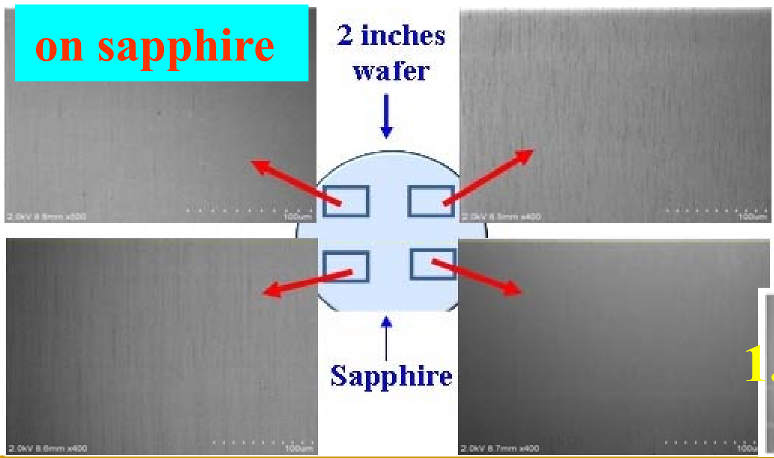
Gas flow directed CVD growth



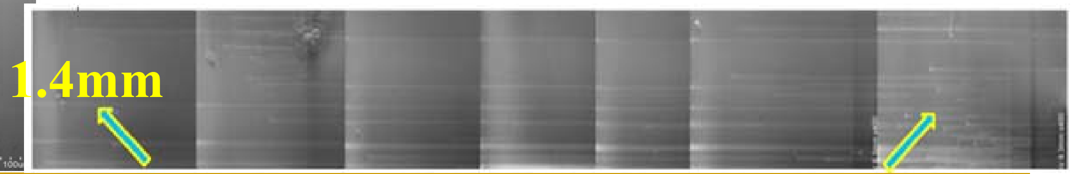
- Tube diameter: 1-2 nm
- Length: > 5 cm
- Spacing: 1-50 μm



Lattice oriented CVD growth

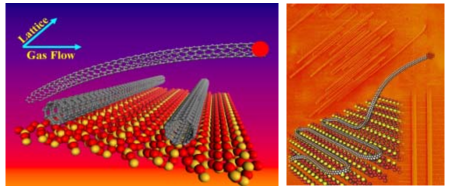


- Diameter: ca. 1 nm
- Length: ca. 1 mm
- Spacing: ~0.2 μm

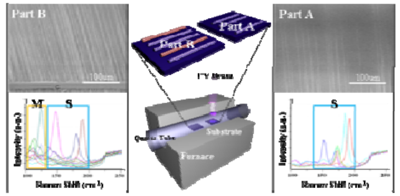


Outline

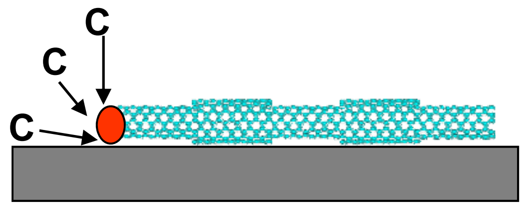
✓ **Controlling Morphology of SWNTs on Surfaces**



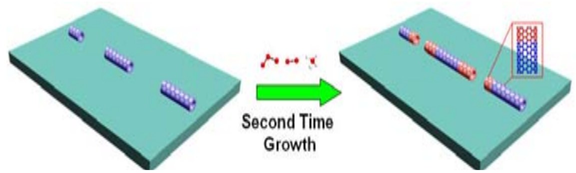
✓ **Direct Growth of Semiconducting SWNT Arrays**

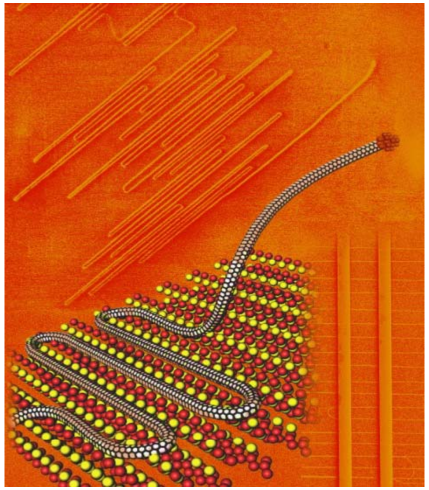


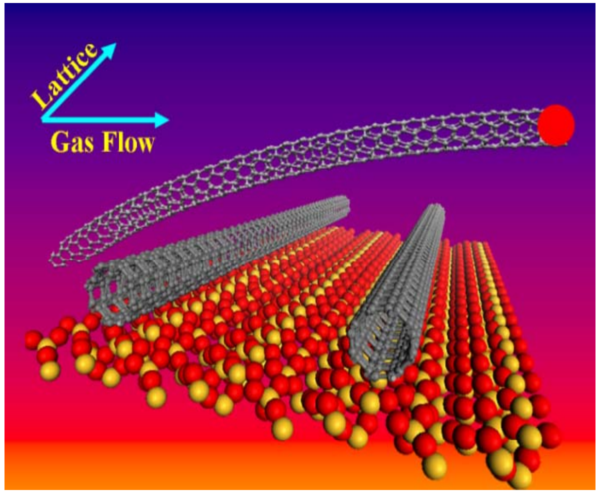
✓ **Tuning Diameters of SWNTs by Temperature**



✓ **Cap-engineering for SWNTs Growth with Controlled Chiralities**

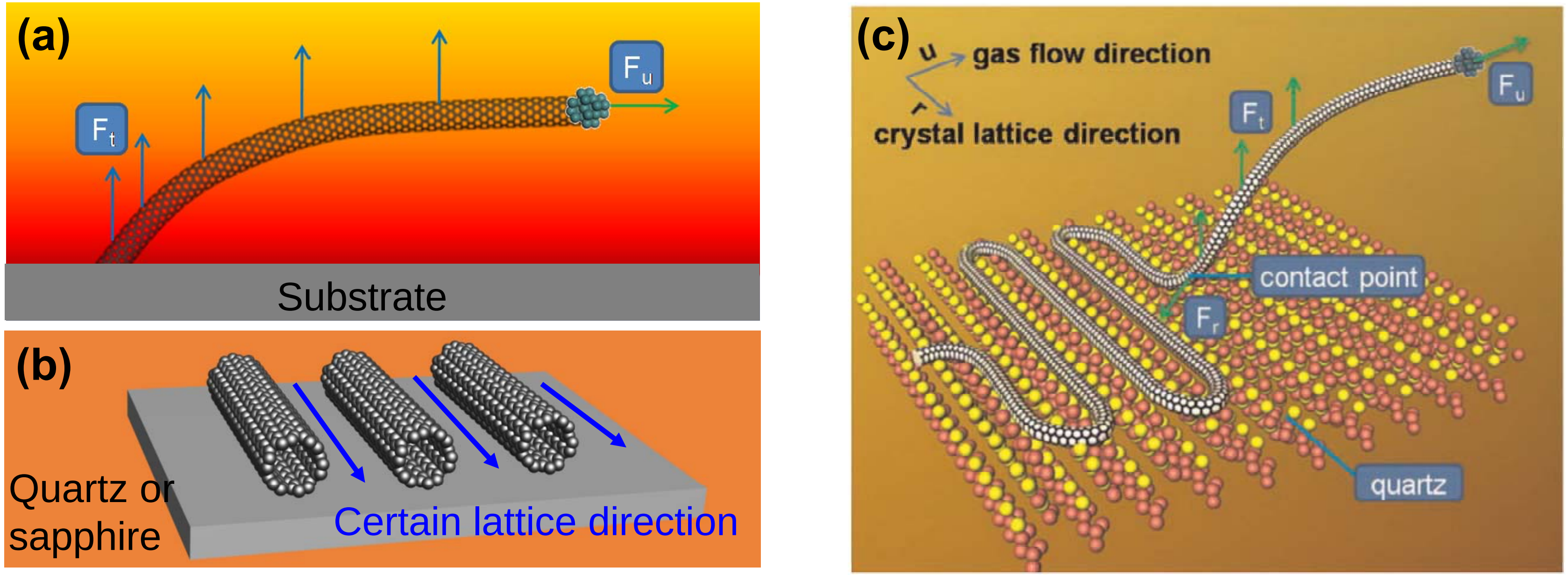






Controlling Morphology of SWNTs on Surfaces by Combing the Two Growth Modes

Growth of serpentine SWNTs

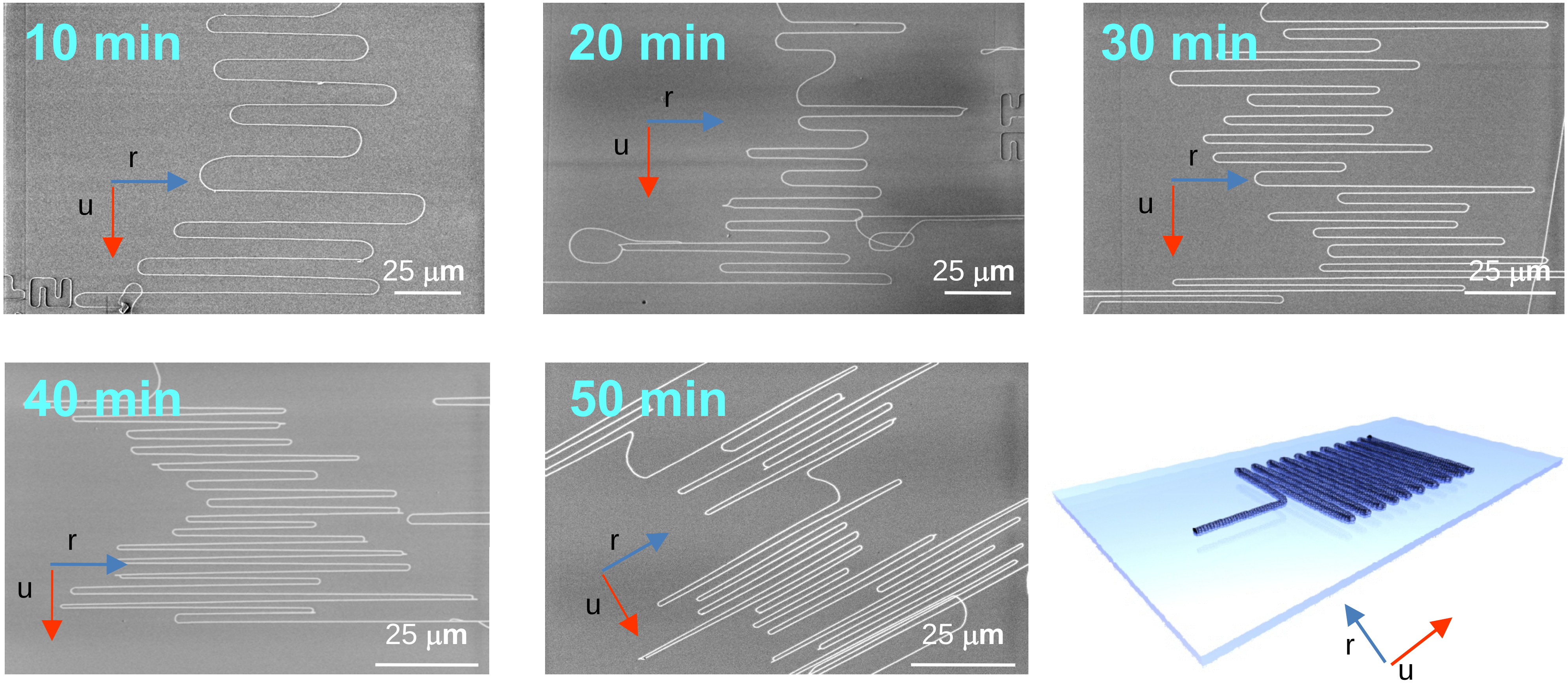


♦The spacing between two parallel sections is mainly determined by the landing rate of the ultralong SWNT.

♦The landing rate can be controlled by cooling rate.

Therefore, the folding density of serpentine SWNTs can be controlled by cooling rate.

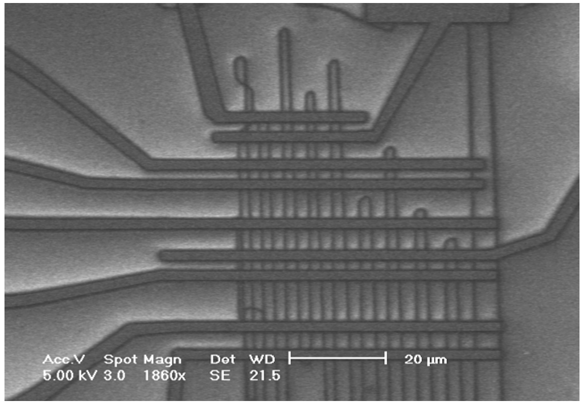
Serpentine SWNTs grown at different cooling rates



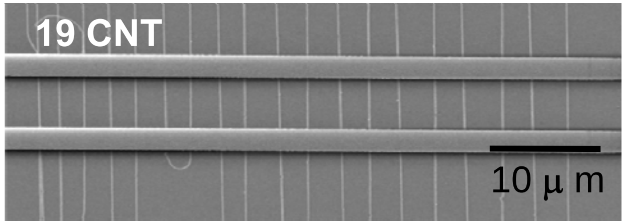
T from 975°C to 775 °C.

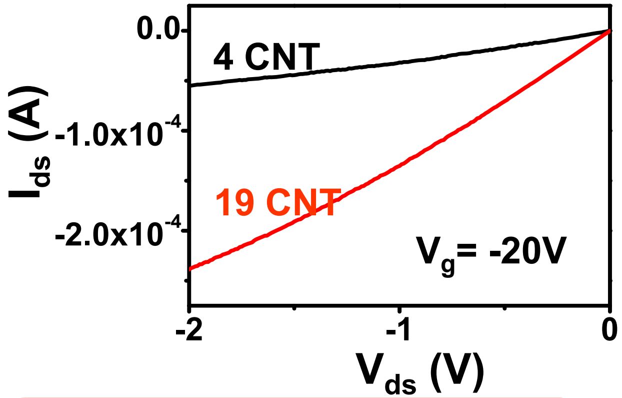
The slower the cooling speed, the higher the tube folding density.

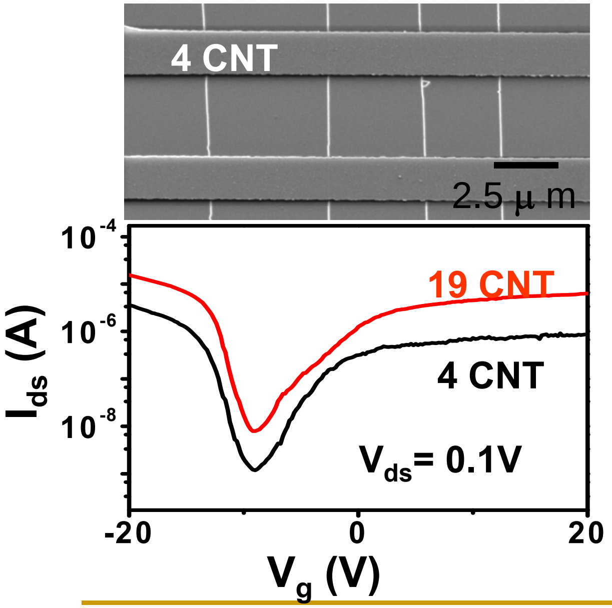
High Performance SWNT-FET with Identical Chirality

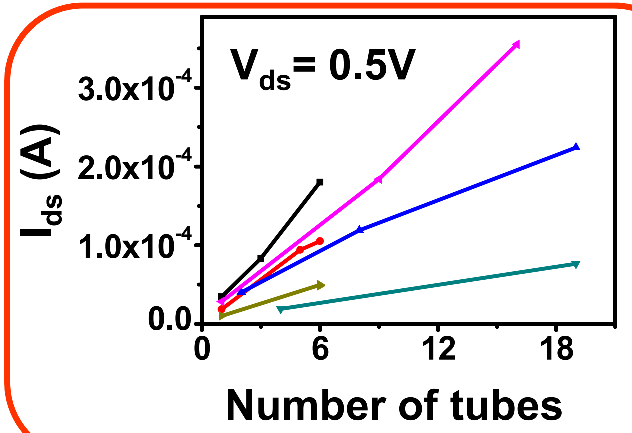


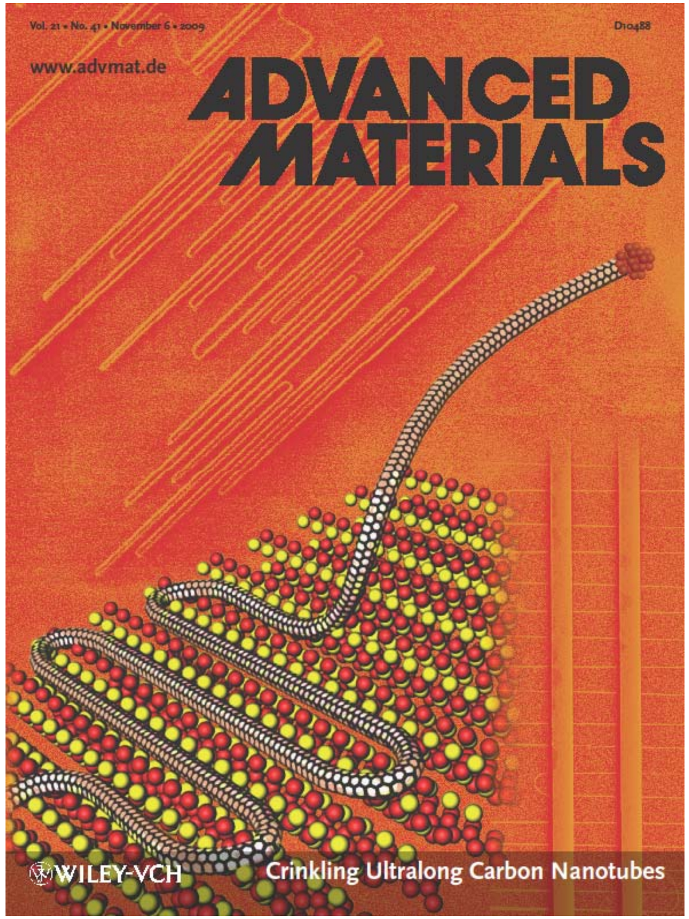
Pd electrode, 800nm SiO_2 gate dielectric





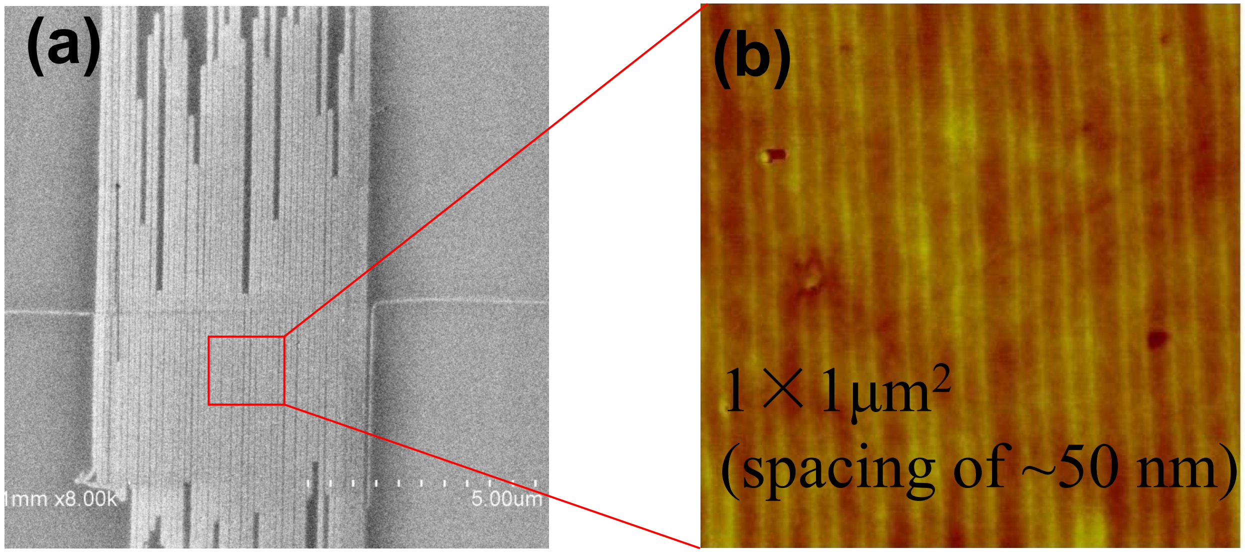


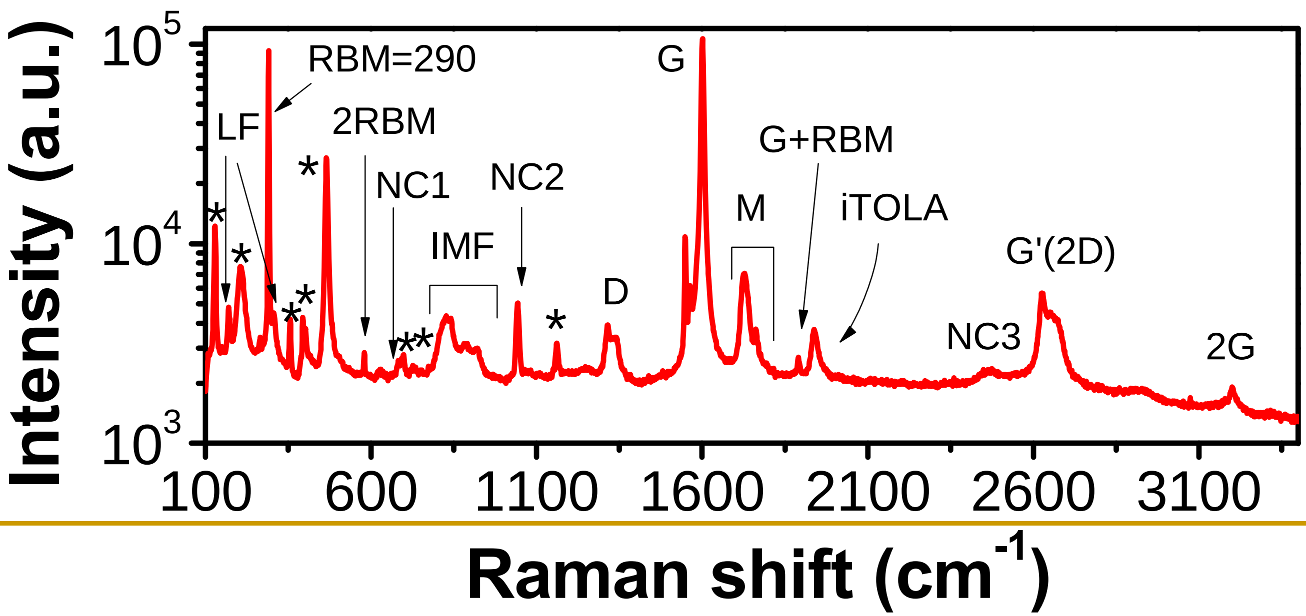




J. Zhang, et. al., Adv. Mater. 2009, 21, 4158-4162. (Inter Front Cover Paper).

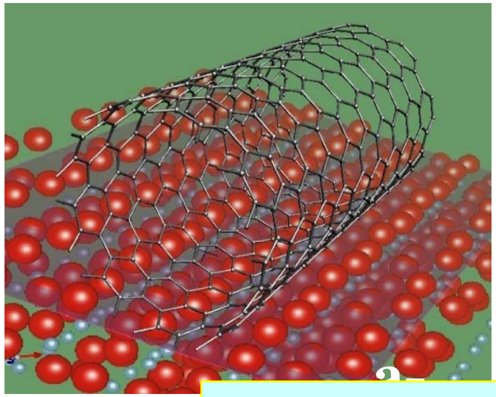
The highest density we have achieved

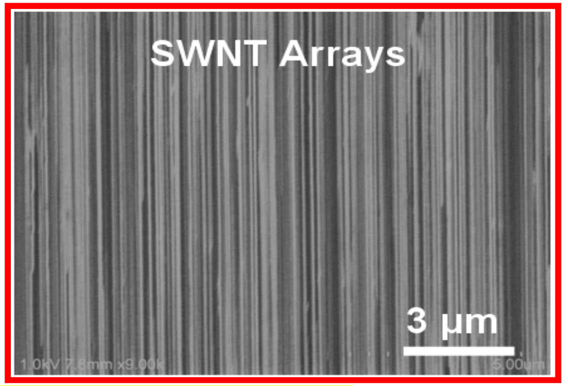




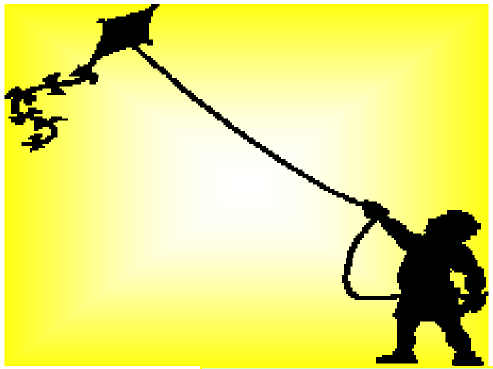
High density of SWNTs make it possible to observed various weak second-order Raman from SWNTs.

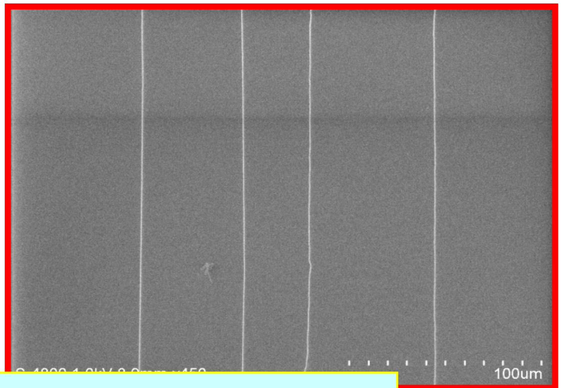
Grow SWNT cross-bars in one batch



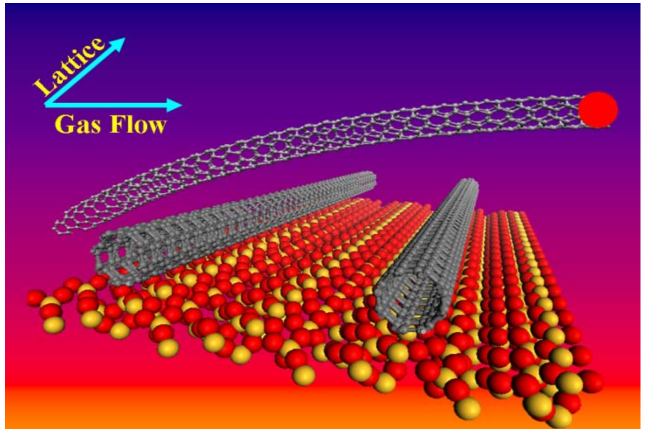


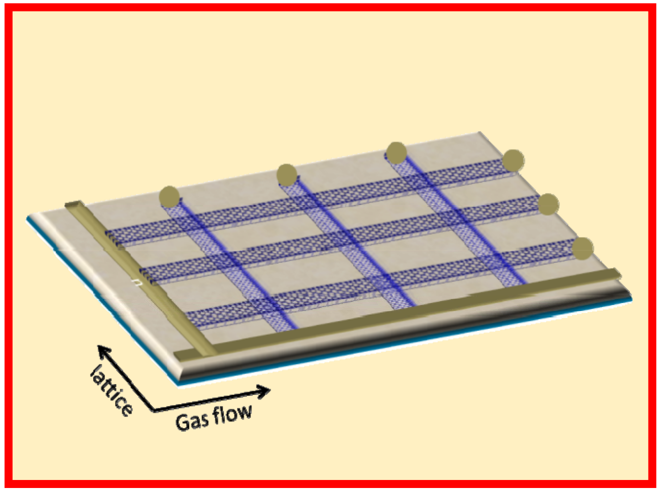
Lattice Directed Growth Mechanism



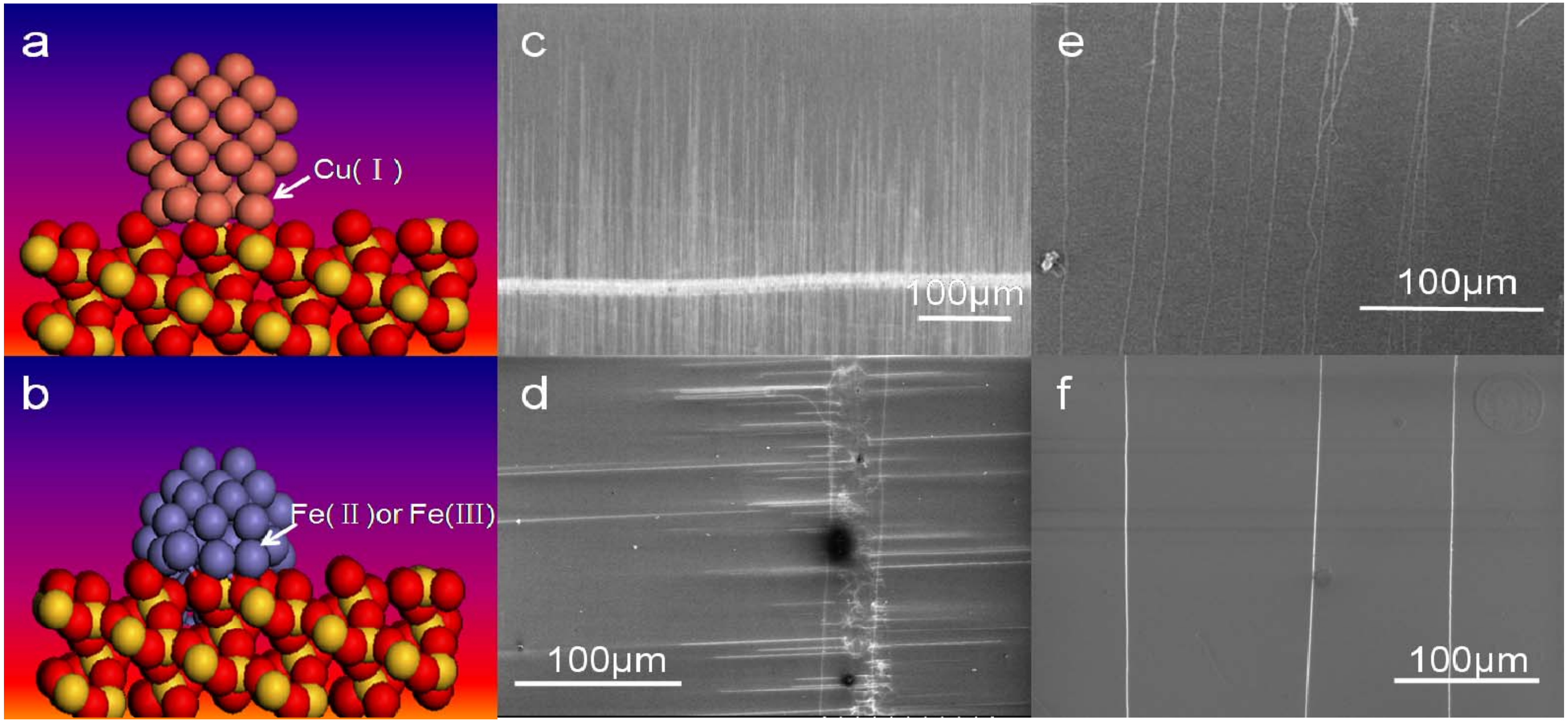


Gas Flow Directed Growth Mechanism





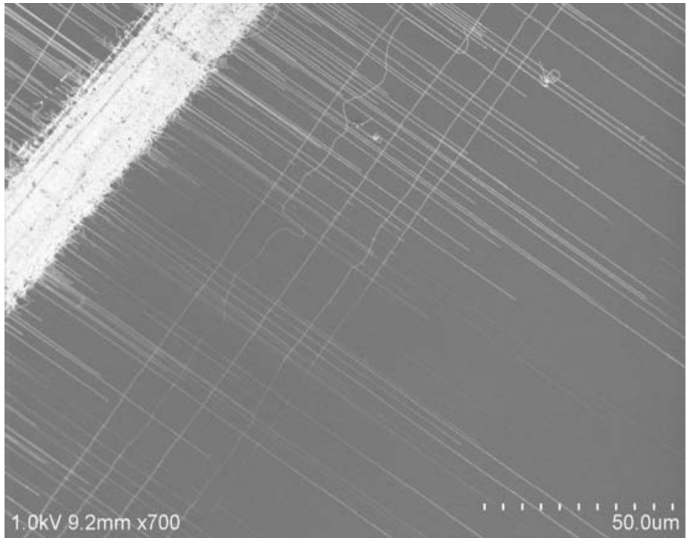
Interaction between Cu, Fe Catlysts and Quartz Surface

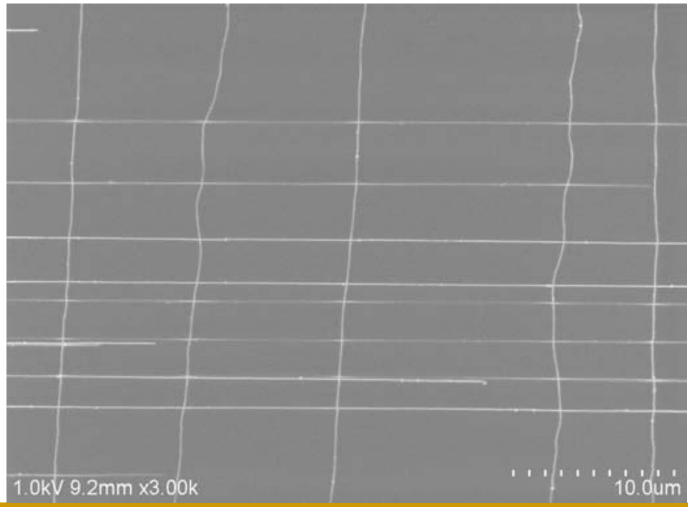


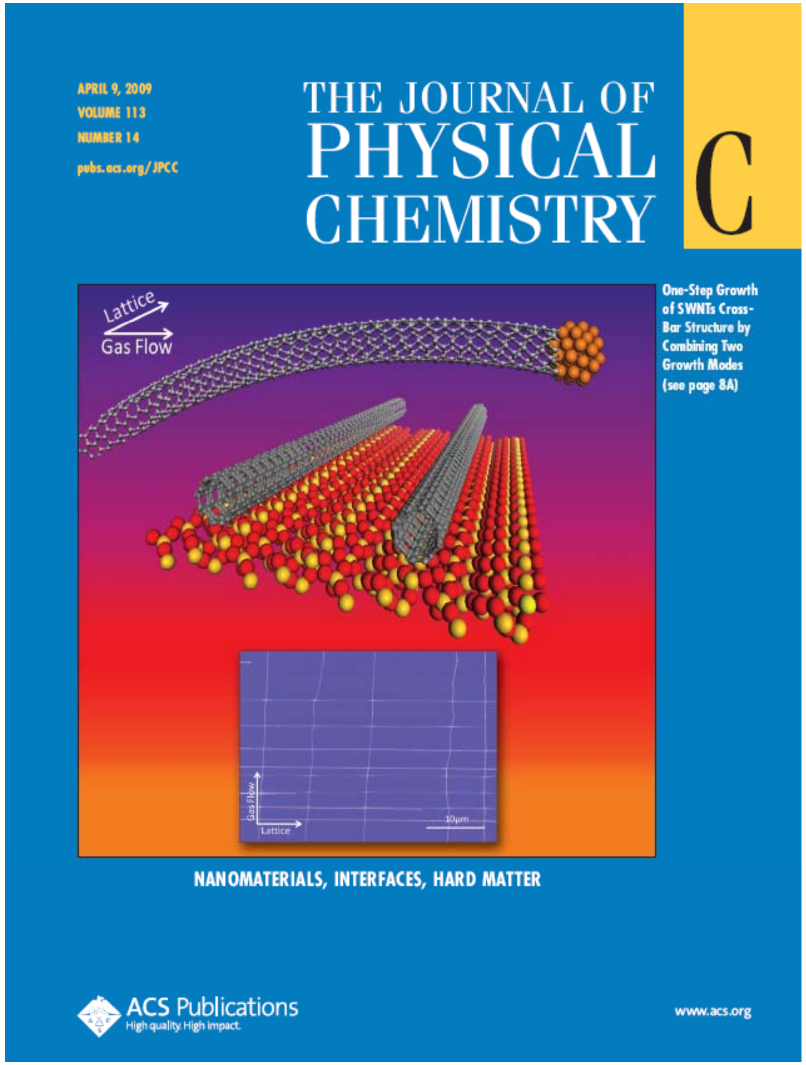
a) and b) illustrate the interaction between Cu, Fe nanoparticles and surface of quartz, the red balls represent oxygen atoms. c) and d) High-magnification SEM image of the lattice assisted SWNTs catalyzed by Cu and Fe. e) and f) Results of gas flow directed growth of carbon nanotubes where Cu and Fe are used as catalysts respectively.

SWNT Cross-bars and Its Potential Application

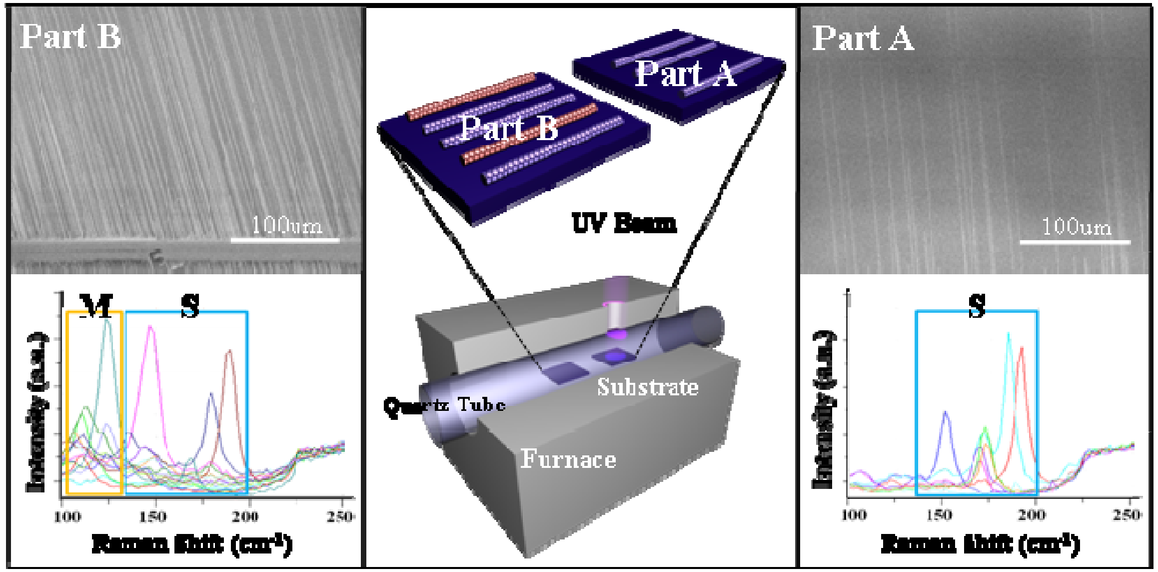
Low temperature favors for lattice oriented growth mode and high T for gas flow directed growth mode. With a moderate 930-950^{o}C, crossbar can be grown.







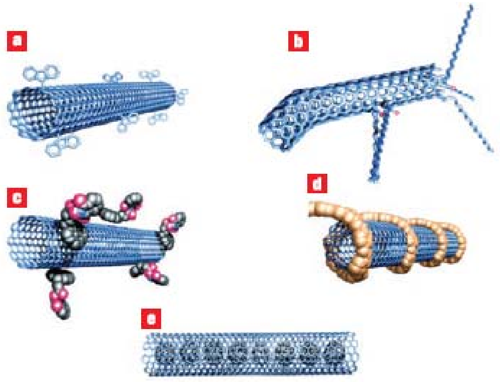
J. Zhang et. al., J. Phys. Chem. C. 2009, 113, 5341-5344 (cover)



Direct Growth of Semiconducting SWNT Arrays by UV Irradiation Assistance CVD

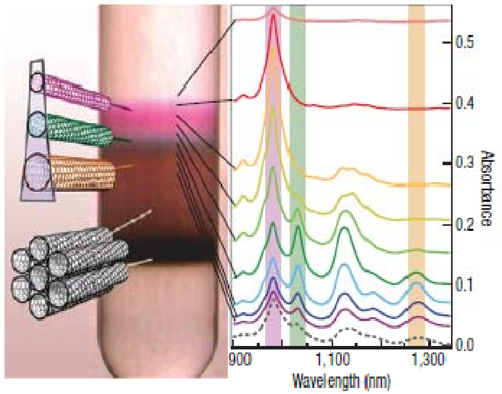
Separation of s-SWNTS and m-SWNTs after Growth

Functionalization



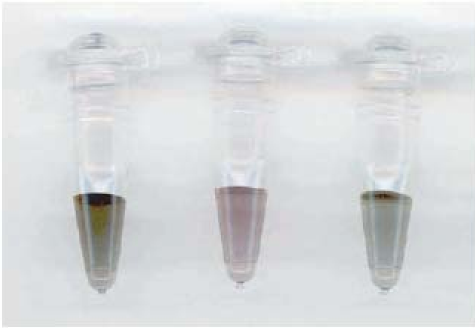
A. Hirsch, Angew. Chem. Int. Ed. , 2002

density gradient ultracentrifugation



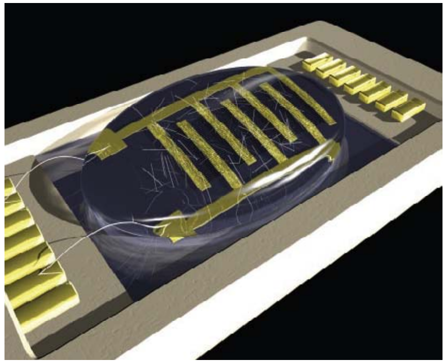
M. S. Arnold, Nature Nanotech. , 2006

Ion-exchange chromatography



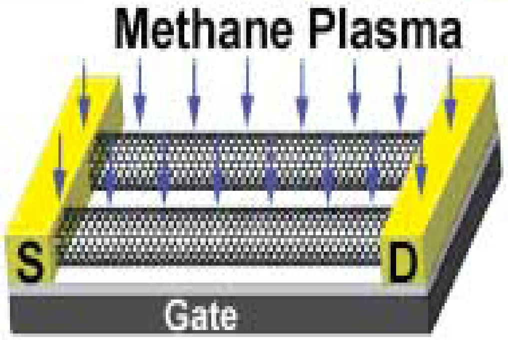
M. Zheng, Nature Mater., *2003*

alternating current dielectrophoresis



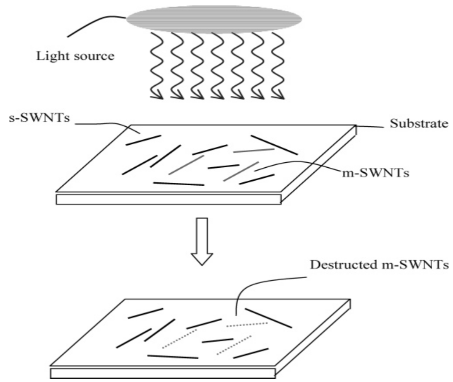
R. Krupke. Science, 2003

gas-phase plasma hydrocarbonation



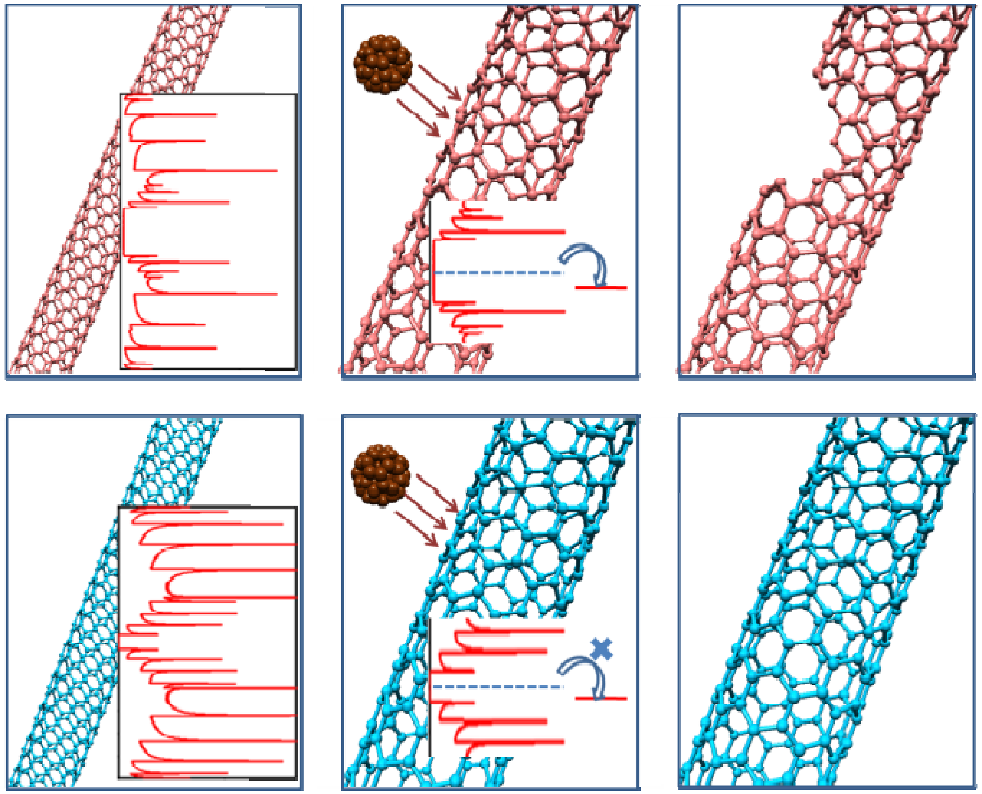
H. J. Dai. Science, 2006

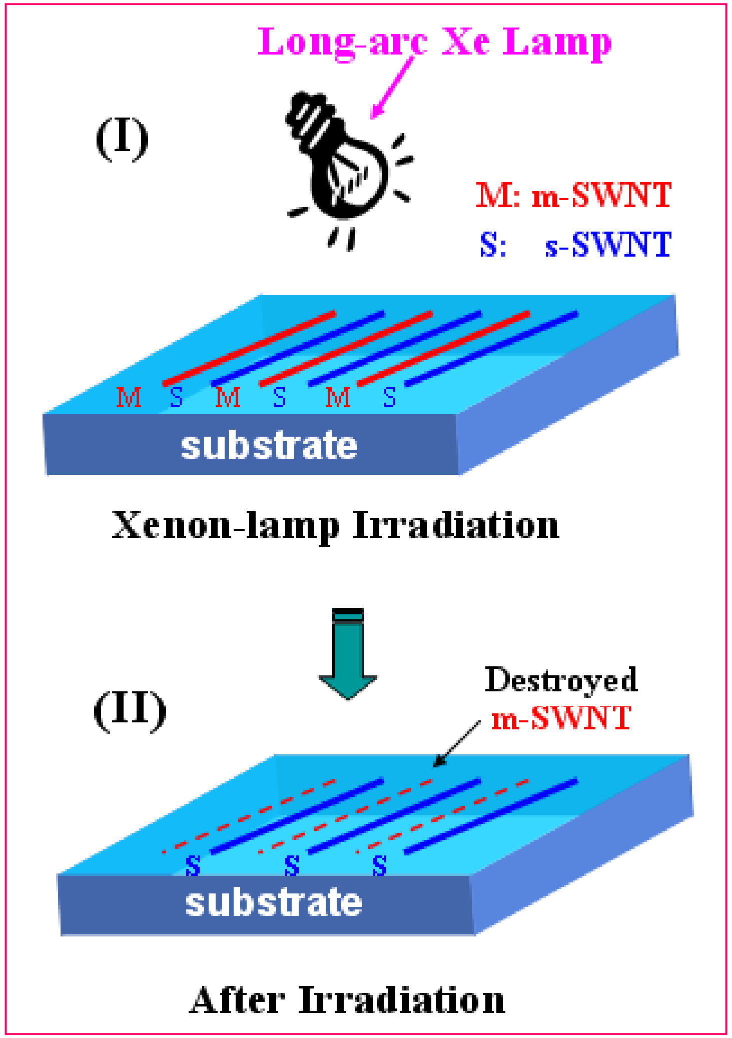
Laser Irradiation



H. J. Huang, J. Phys. Chem. B, 2006

Why s-SWNTS and m-SWNTs can be Separated

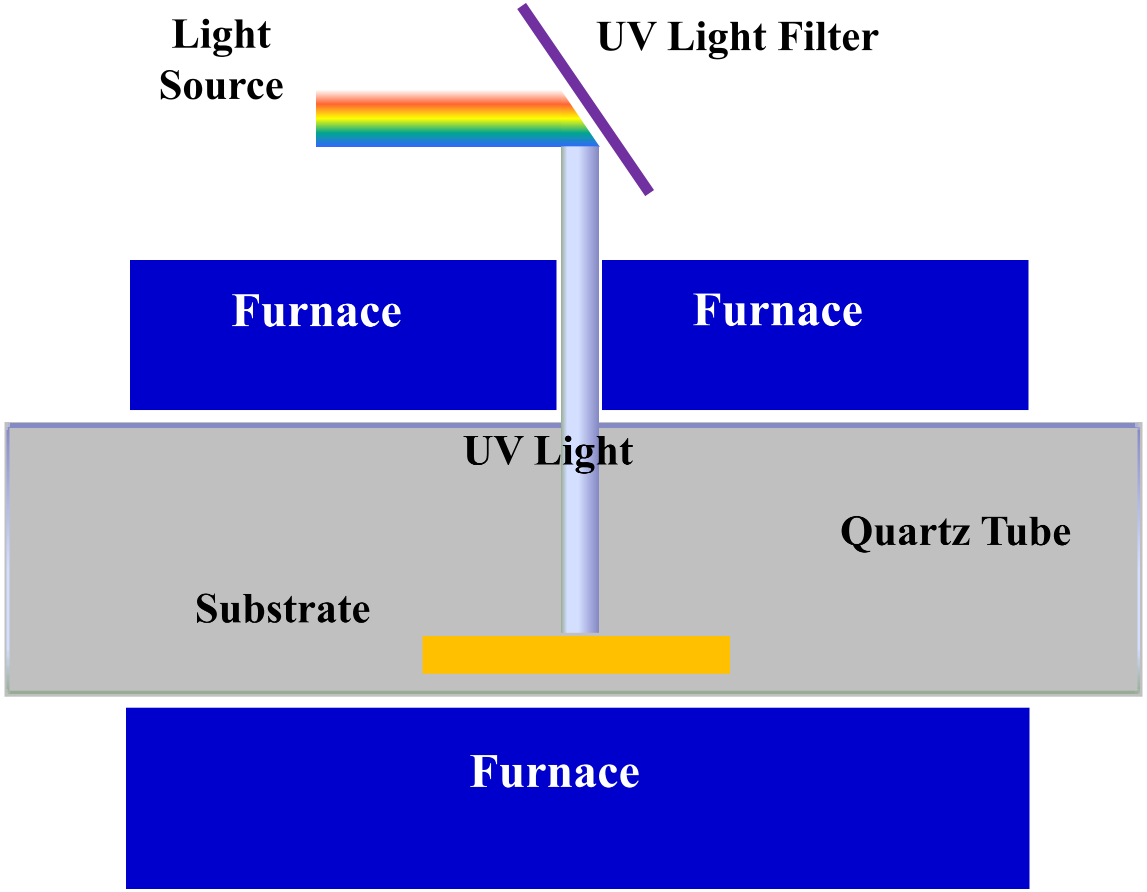




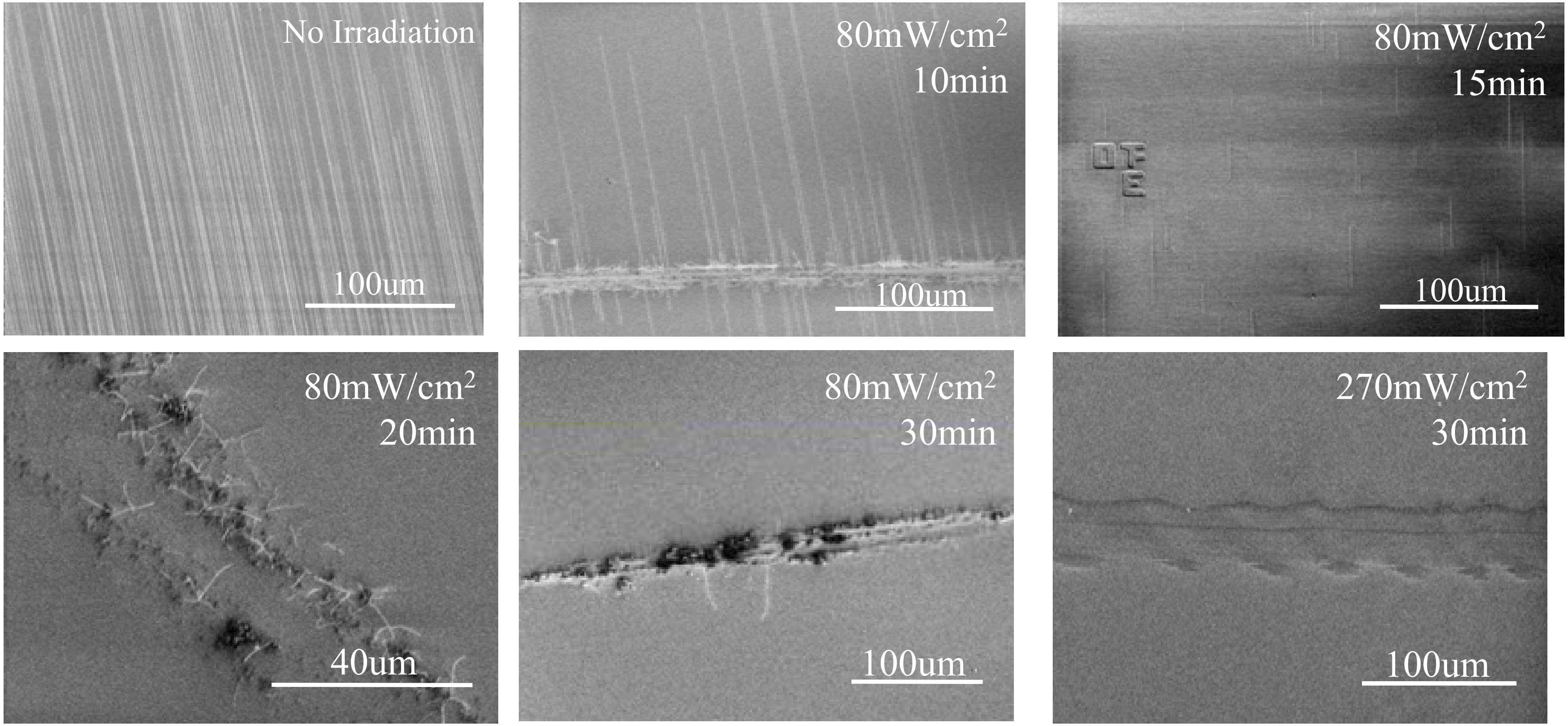
When a reactant comes near the SWNT, the electron can transfer from the metallic SWNT, but cannot transfer from the semiconducting SWNT. After that, the metallic SWNT can be damaged and the semiconducting SWN still survived .

J. Zhang, et. al., J. Phys. Chem. C 112, 3849, (2008)

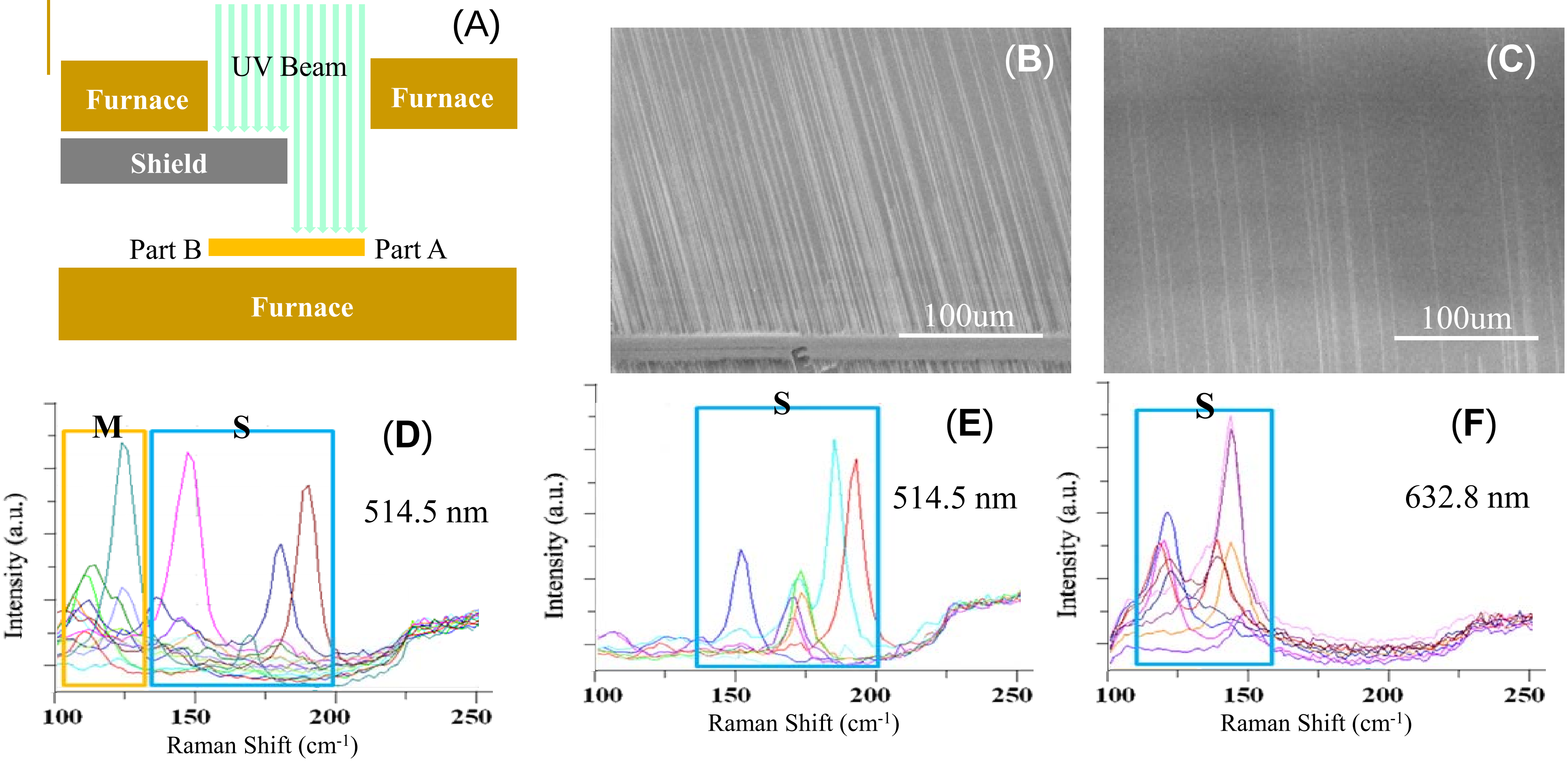
Setup of Our Home-Made CVD System



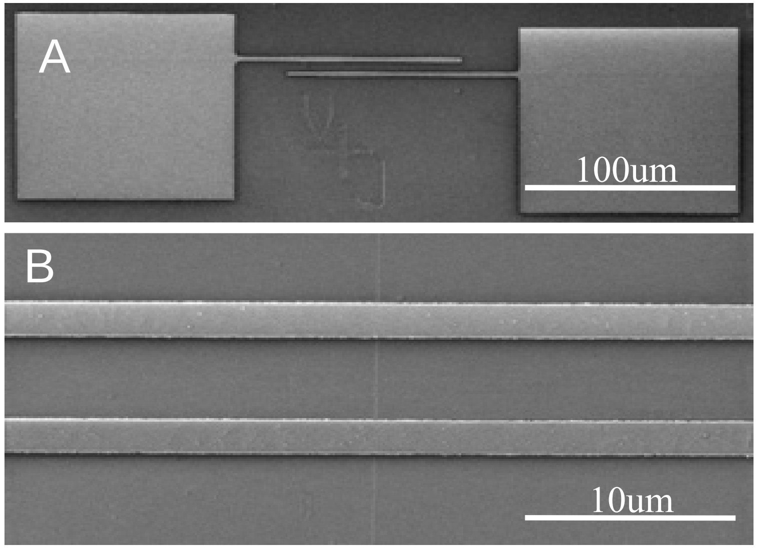
SEM images of SWNTs arrays under different irradiation time

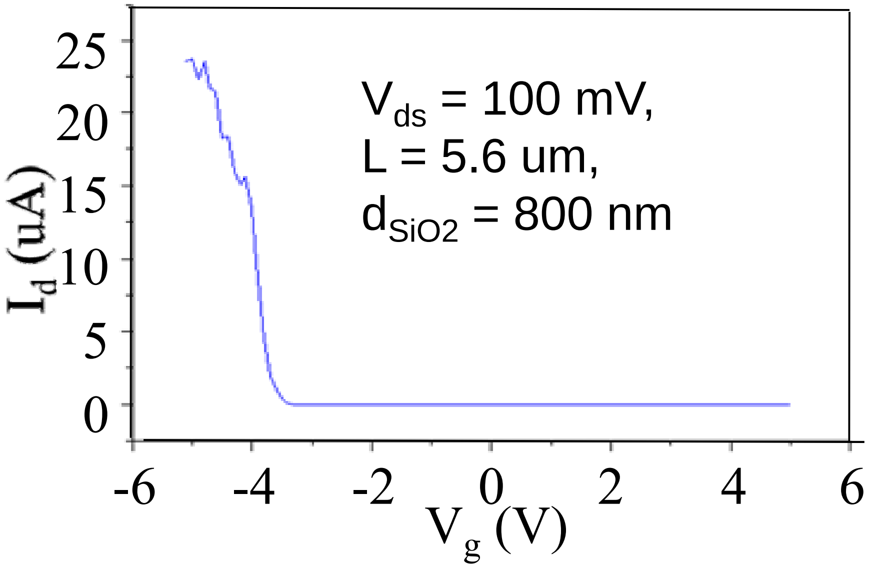


When UV beam acted on the substrate, the density of the SWNT array decreased obviously. From above, the shorter the irradiation time, the longer and denser the SWNTs were. If we continued increasing the irradiation time or the irradiation intensity, SWNTs would become shorter and shorter, and disappeared eventually



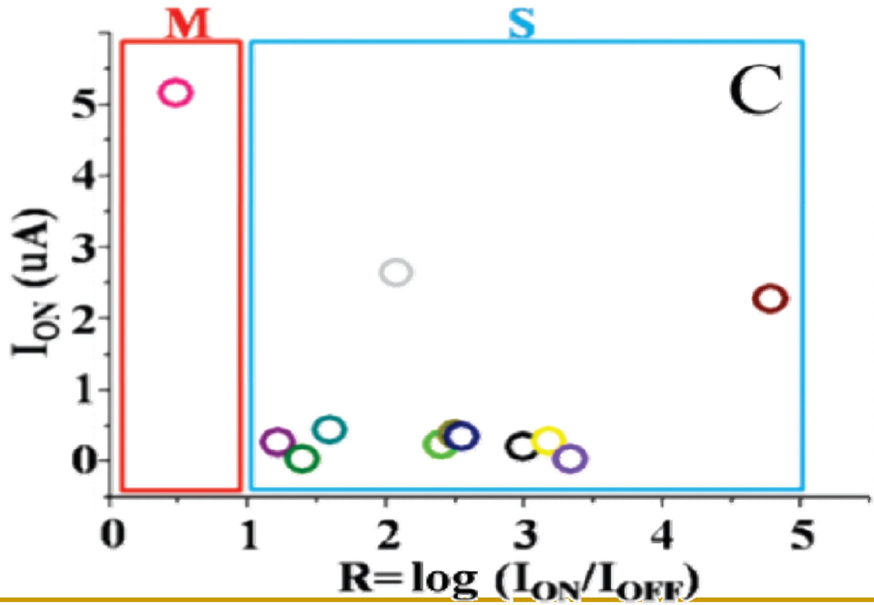
(A) Sketch map of the comparison experiment for SWNT growth with and without UV irradiation. (B)/(C) SEM image of the growth result without/with UV irradiation. (D) Raman spectrum for part B with 514.5 nm excitation. (E)/(F) Raman spectrum for part A with 514.5/632.8 nm excitation. The metallic SWNTs signals were collected in the yellow rectangle while the semiconducting SWNTs signals were collected in the blue rectangle separately for all the three spectra.



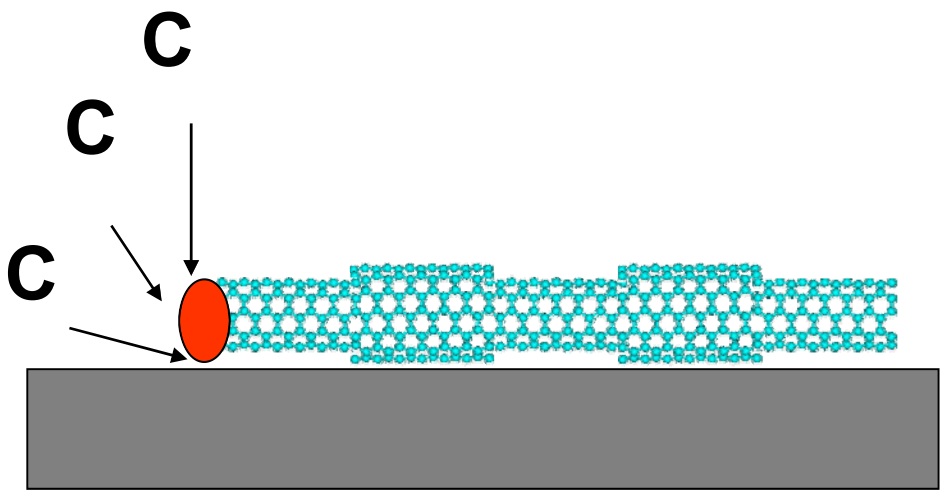


Raman spectra demonstrated an amazing result that almost 100% SWNTs were semiconducting.

Electrical measurement data showed that 21 out of 22 SWNTs (~95%) were semiconducting.



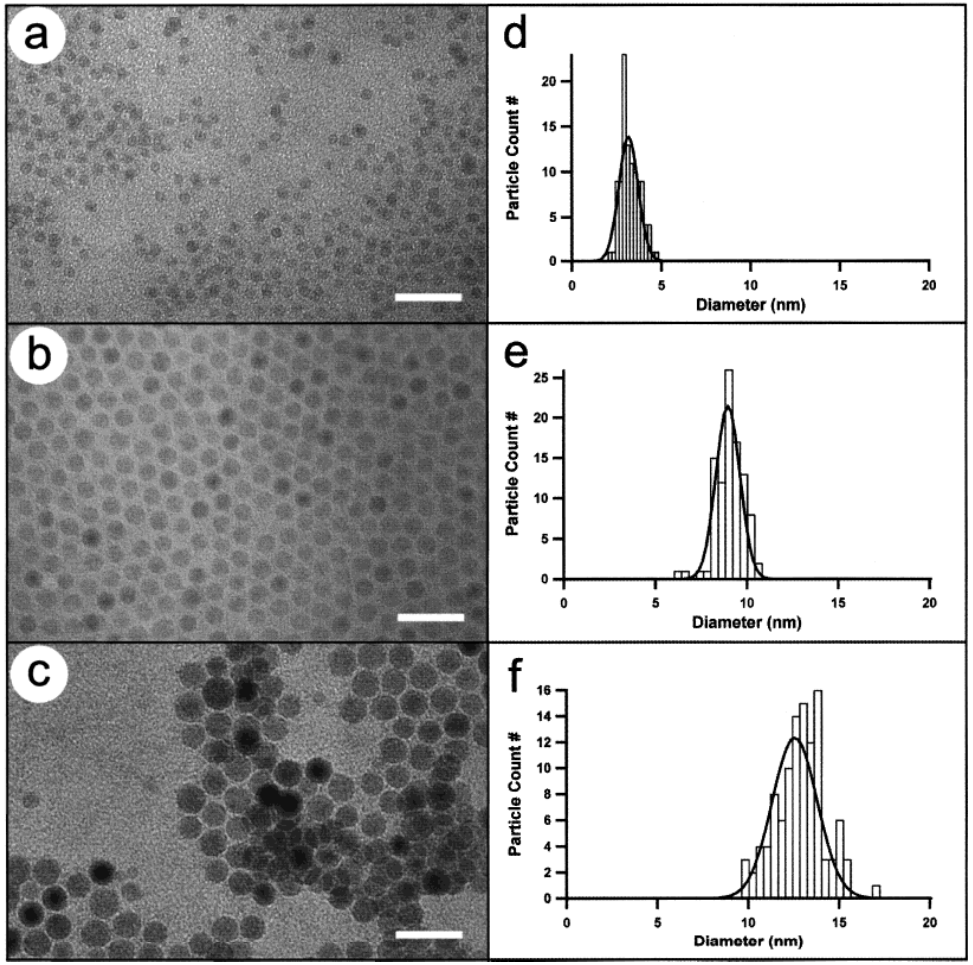
J. Zhang et al., J. Am. Chem. Soc., 2009, 131, 14642-14643



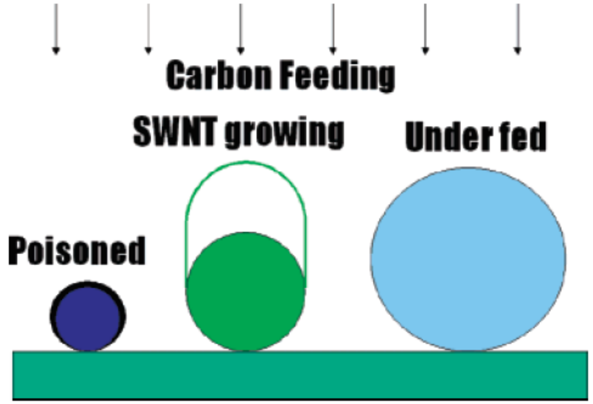
Tuning Diameters of SWNTs by Temperature-oscillation CVD growth

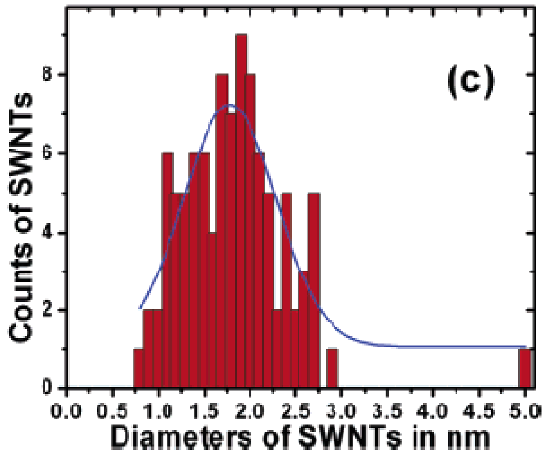
Controlling Diameters of SWNTs

By Catalyst Particle



By Carbon Feeding

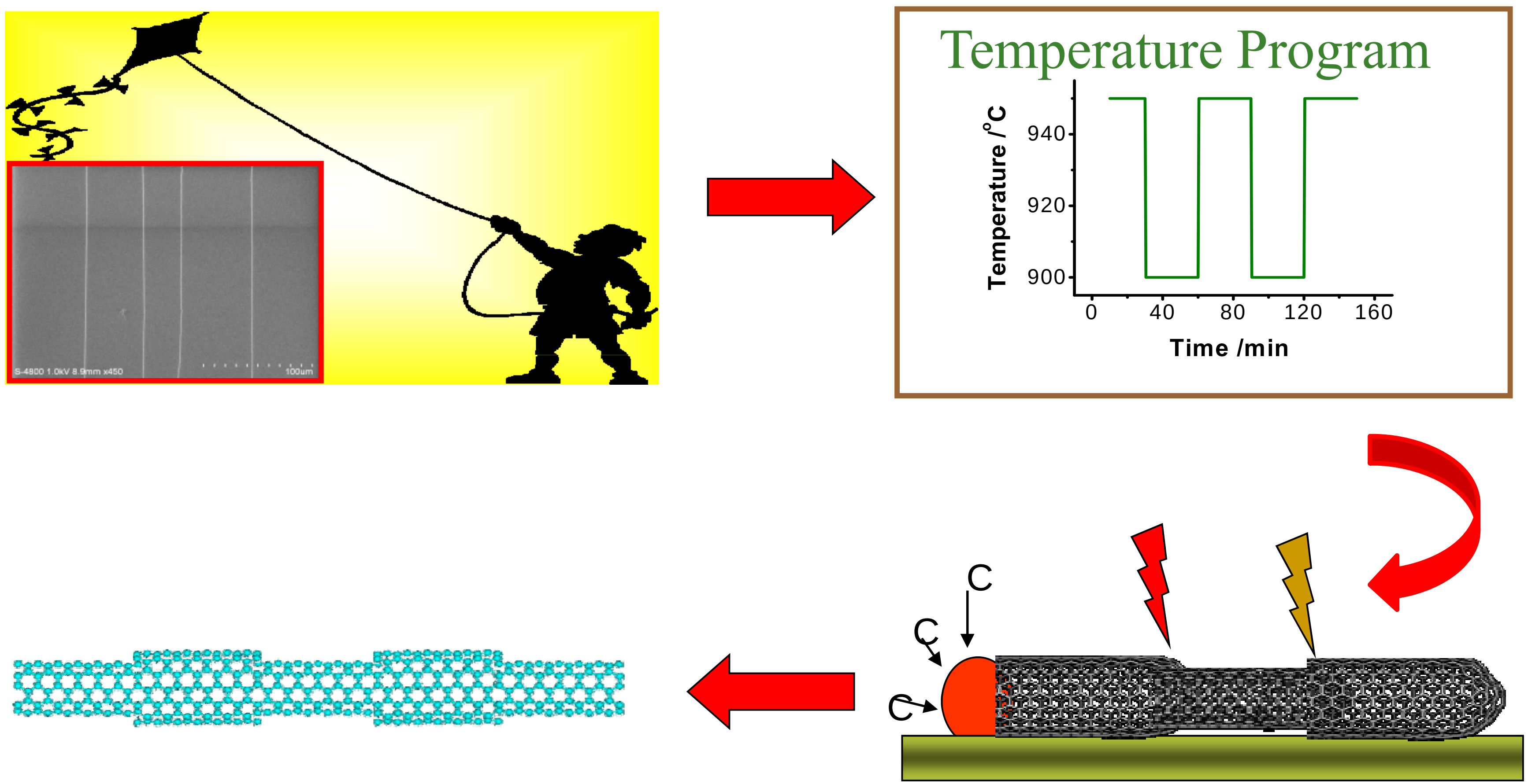




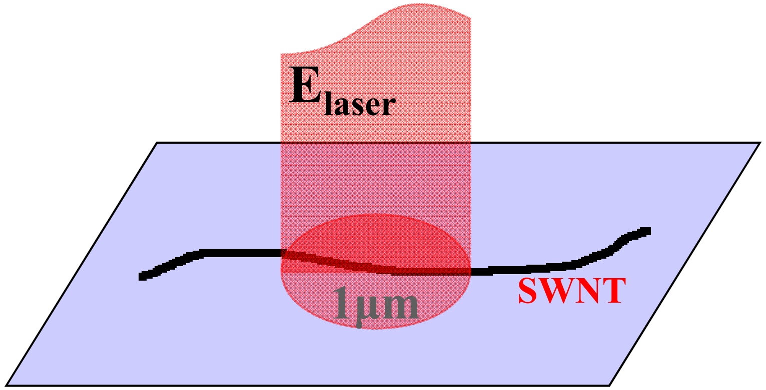
J. Phys. Chem. B. 2002,106, 2429-2433

J. Phys. Chem. B. 2006,110,20254-20257

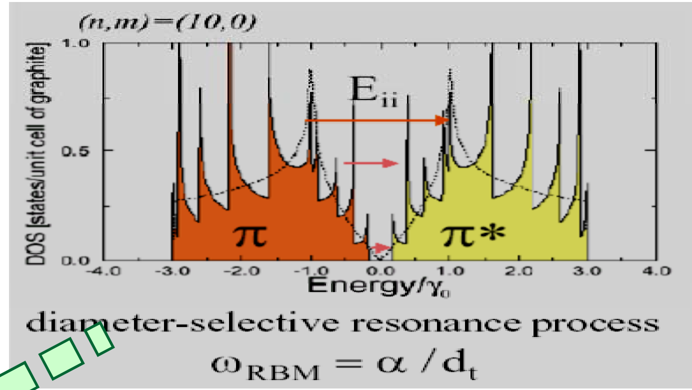
Our Approach: Tune the Diameter of SWNTs by Temperature



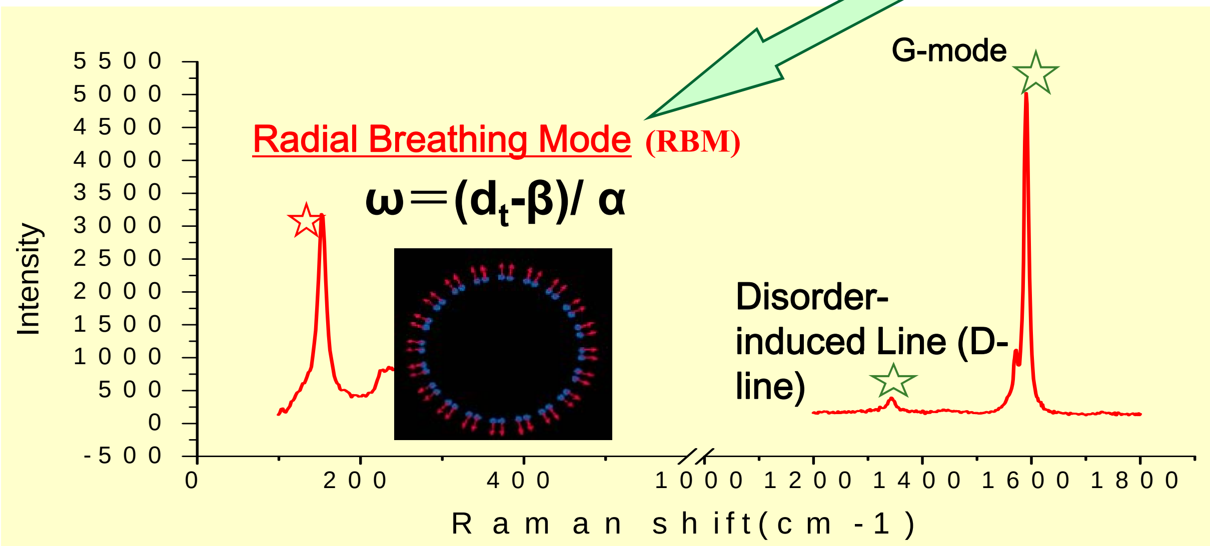
Micro-Resonance Raman Spectrum of Individual SWNTs

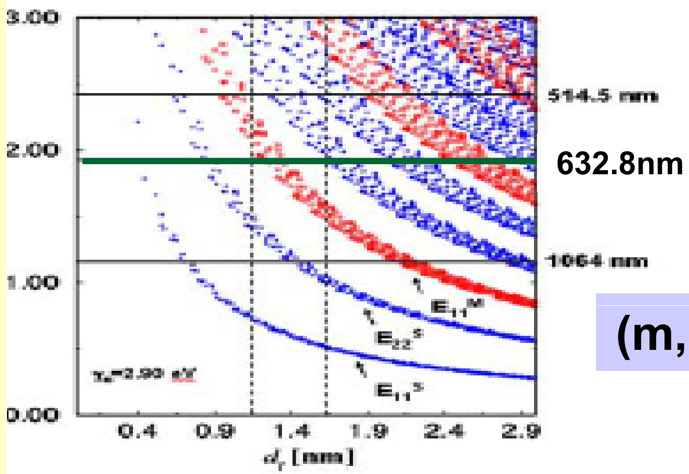


Micro-Raman spectroscopy



Resonance condition: E_{laser}=E_{ii}

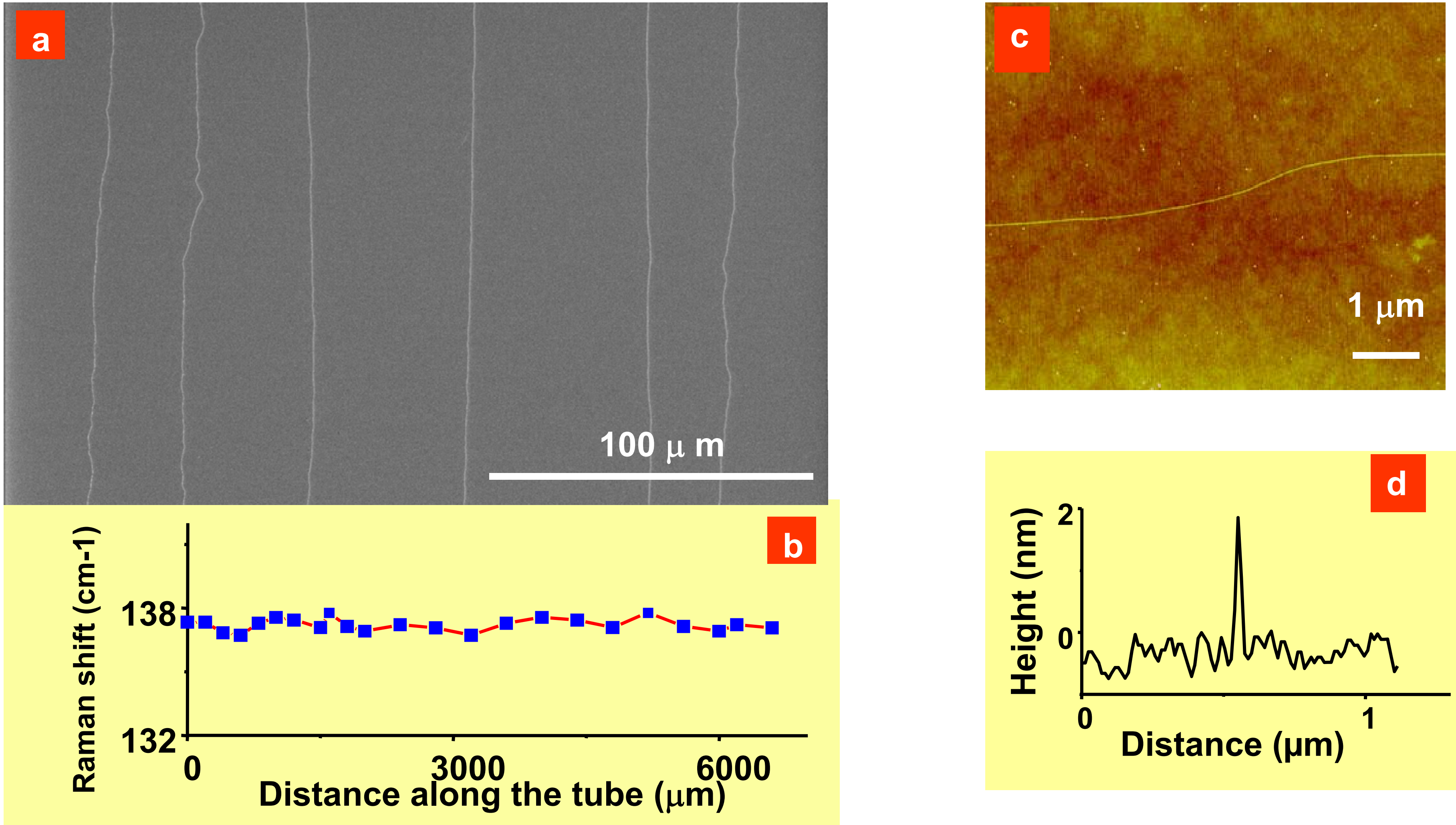




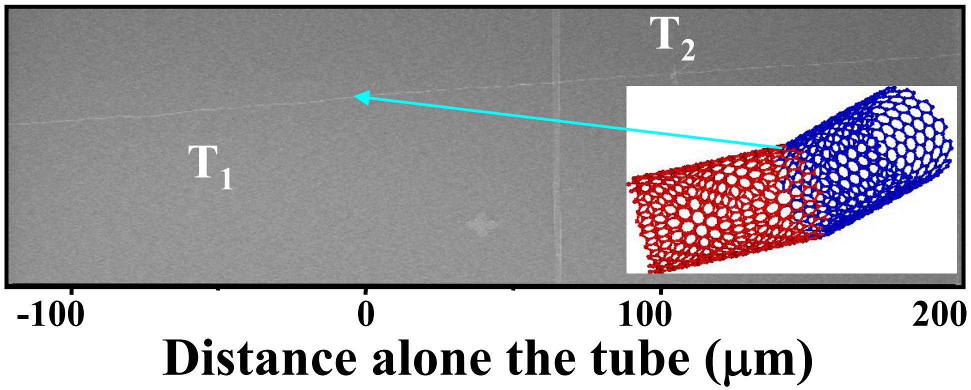
(m,n)

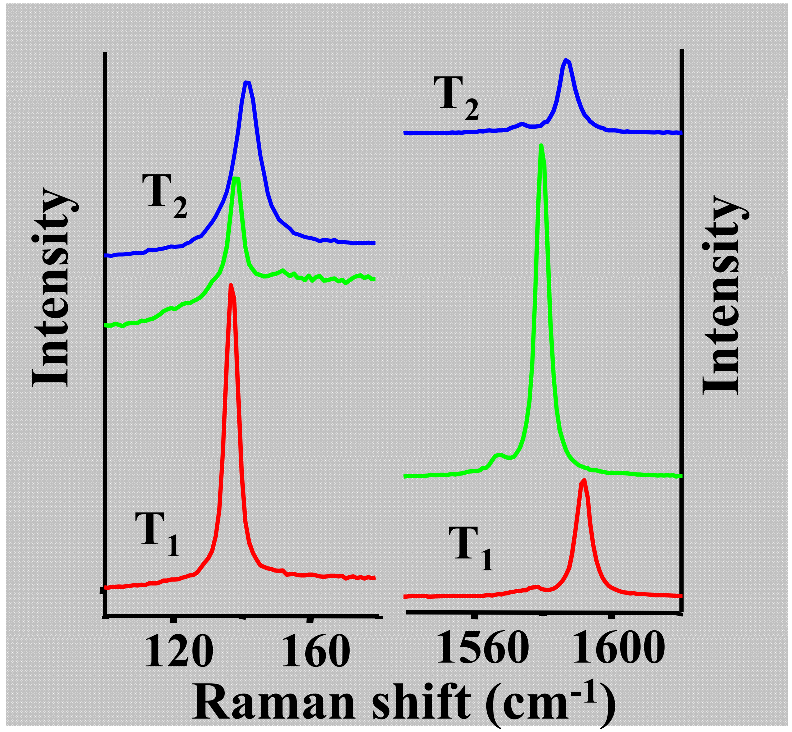
A power tool for both the atomic and electronic structure of SWNT !

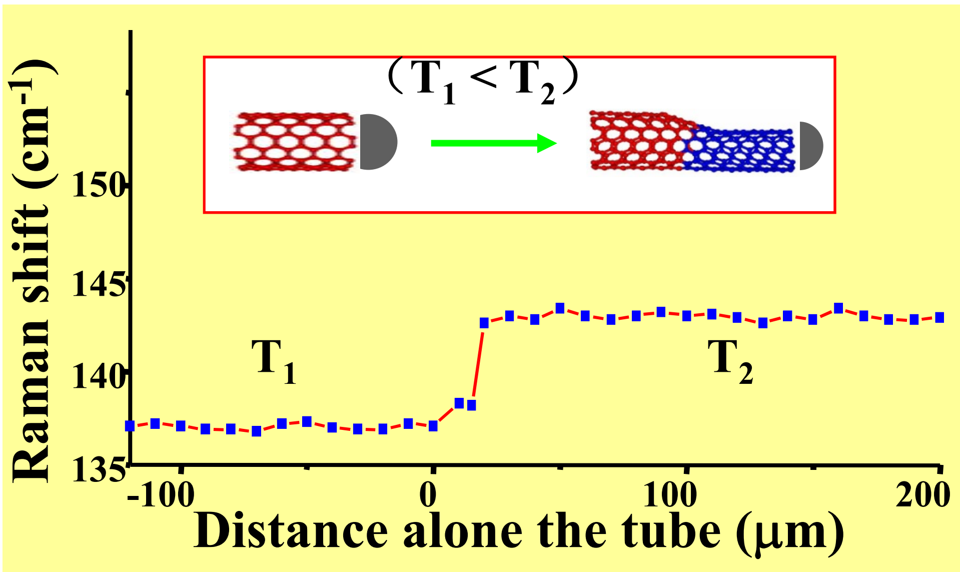
Constant-temperature CVD

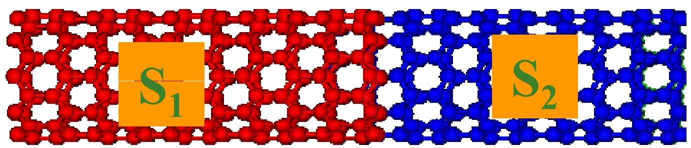


SWNTs Grown by one Time Temperature Oscillated CVD (From 900°C to 950°C)



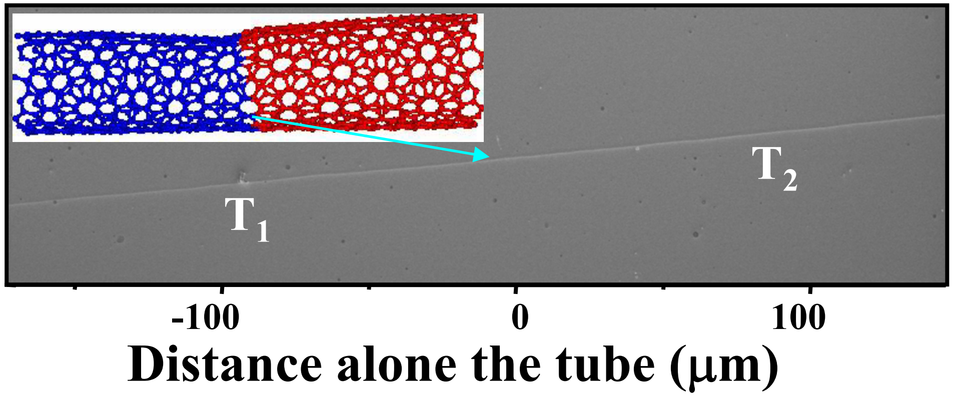


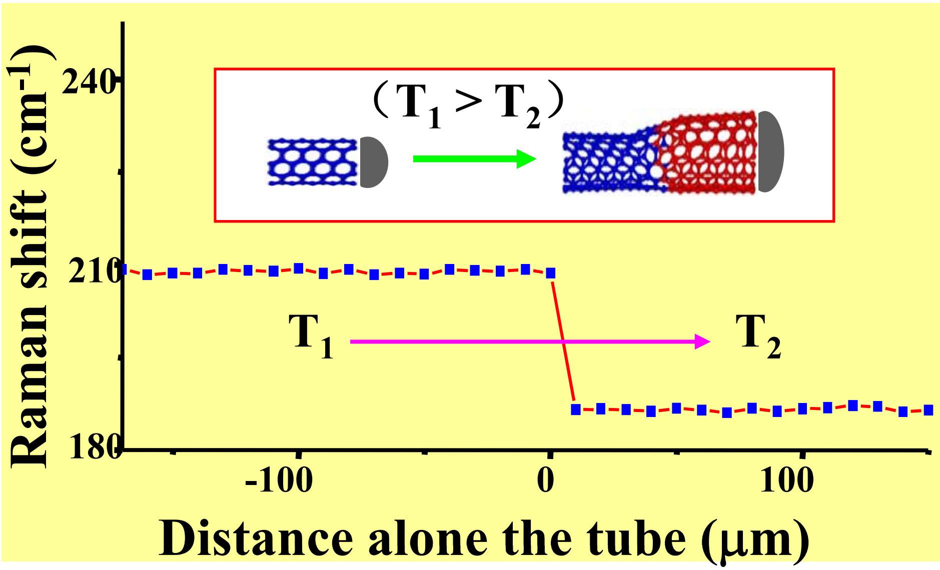


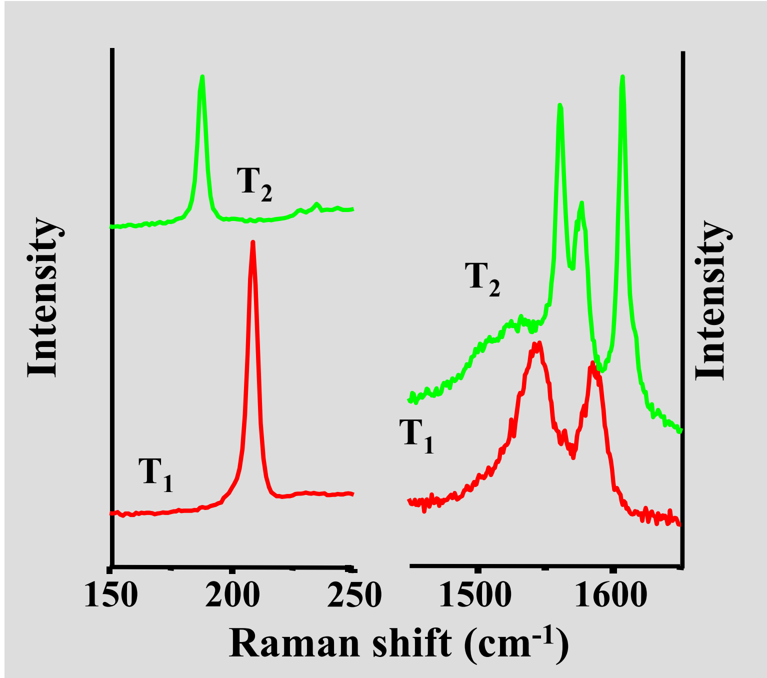


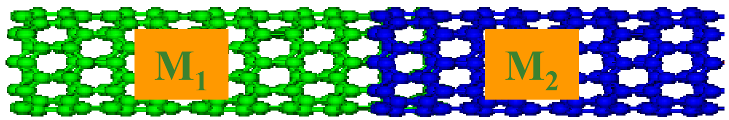
Semiconducting—Semiconducting Nanojunction

SWNTs Grown by one Time Temperature Oscillated CVD (From 950ºC to 900ºC)





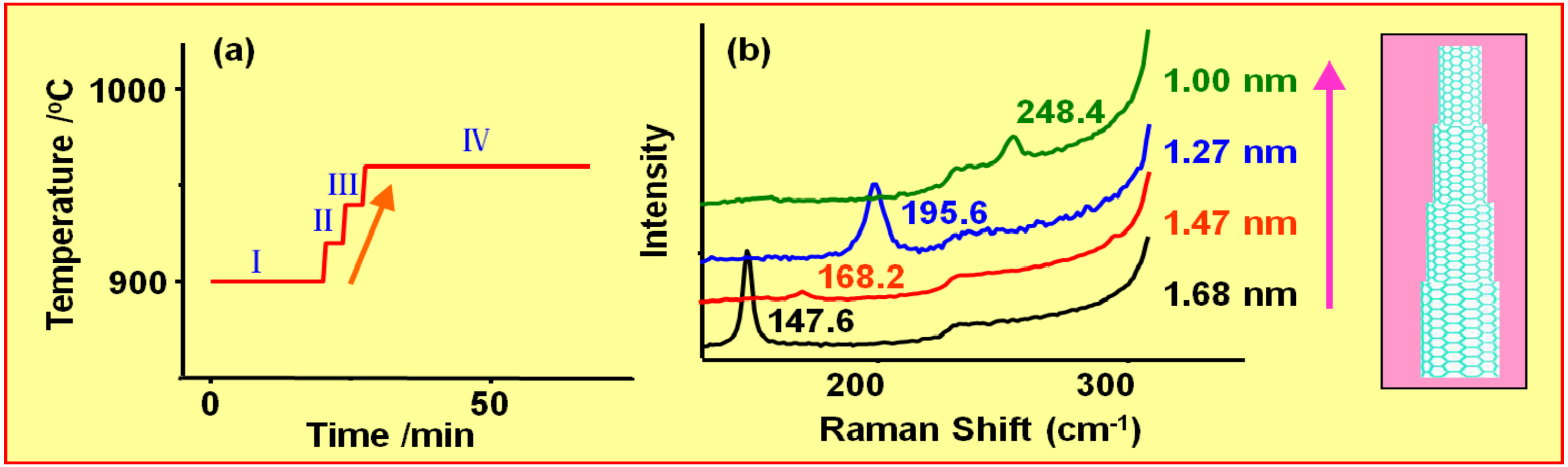


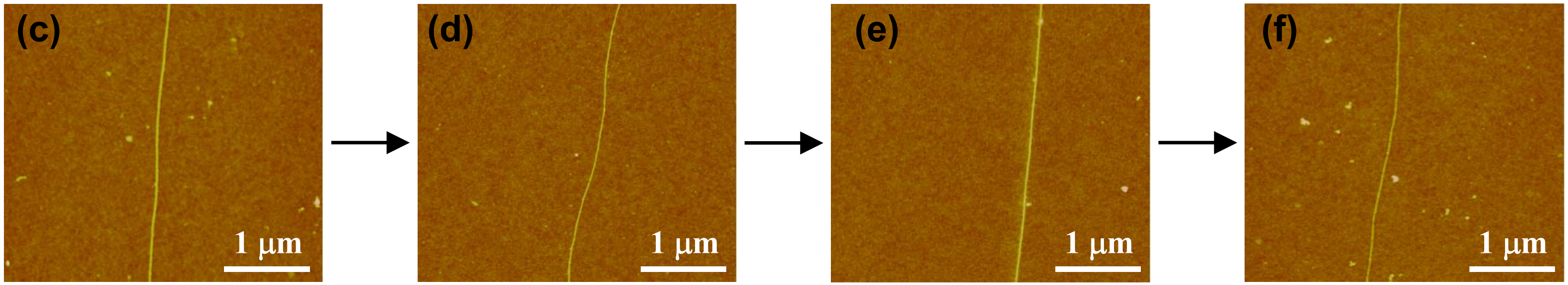


Metallic—Metallic Nanojunction

Controlled Thinning of SWNTs via Temperature Step-Up

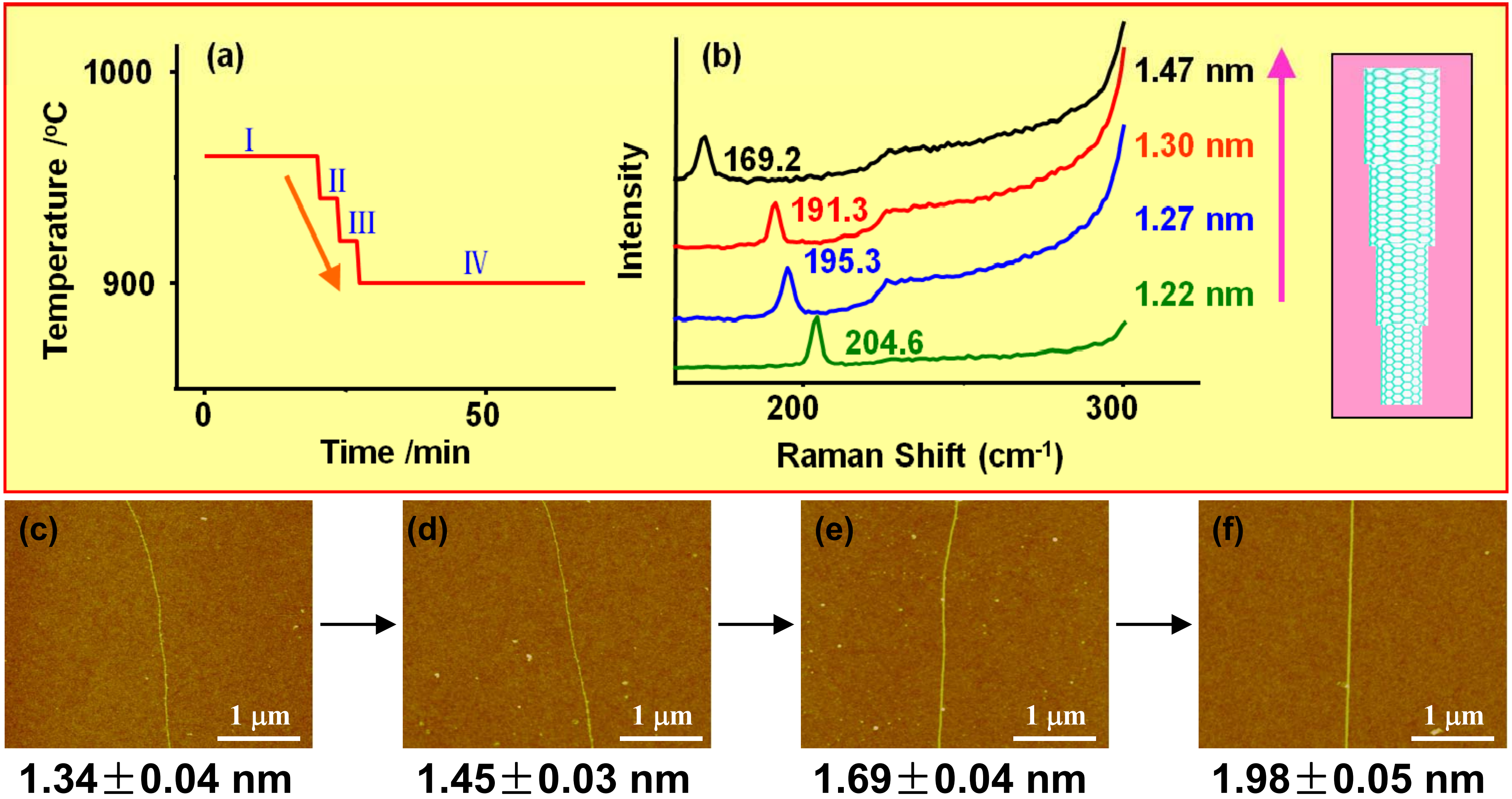
900 °C→ 920 °C→ 940 °C→ 960 °C





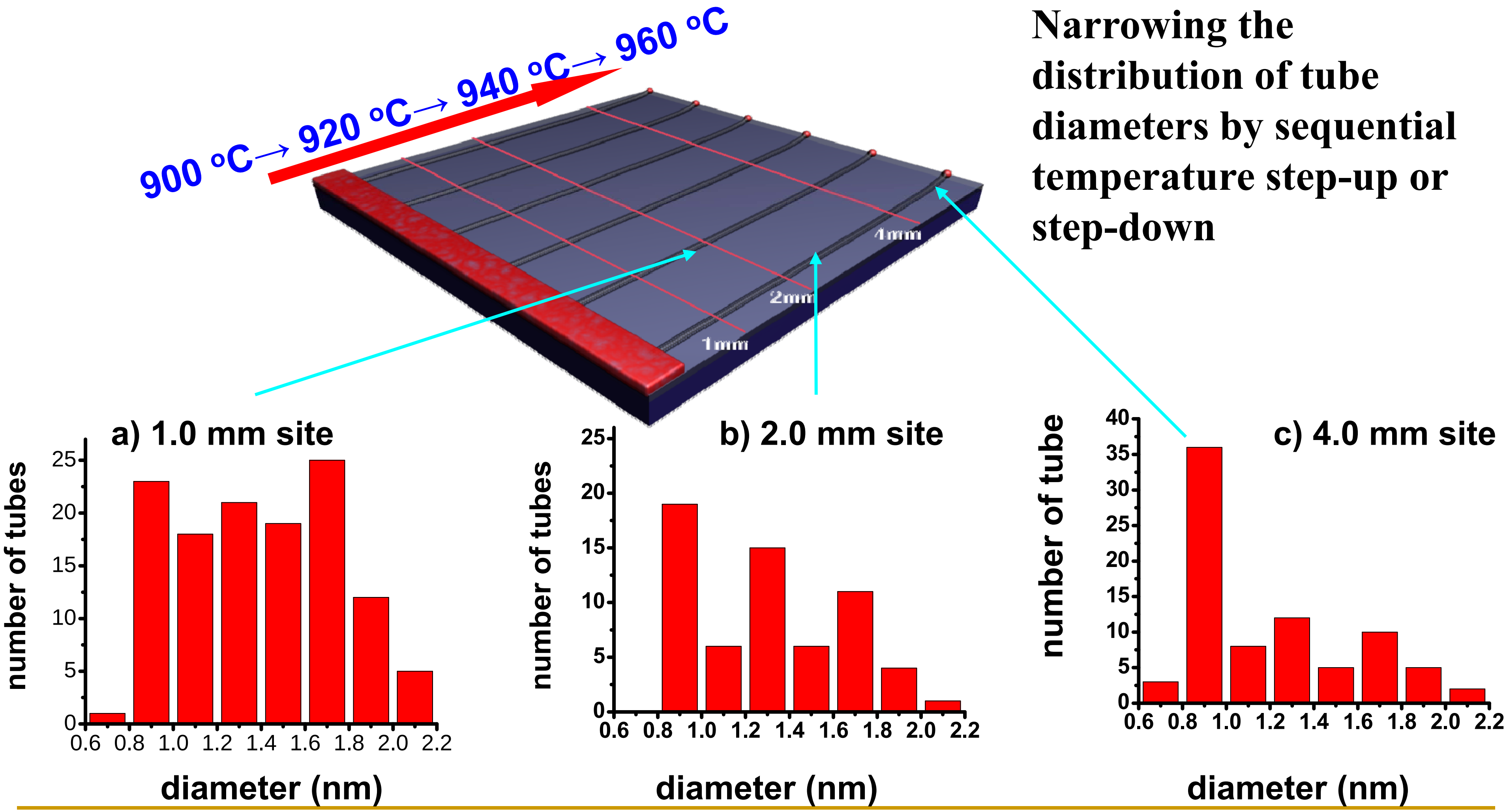
2.04±0.06 nm → 1.86±0.05 nm → 1.76±0.03 nm → 1.32±0.04 nm

Controlled Thickening of SWNTs via Temperature Step-Down



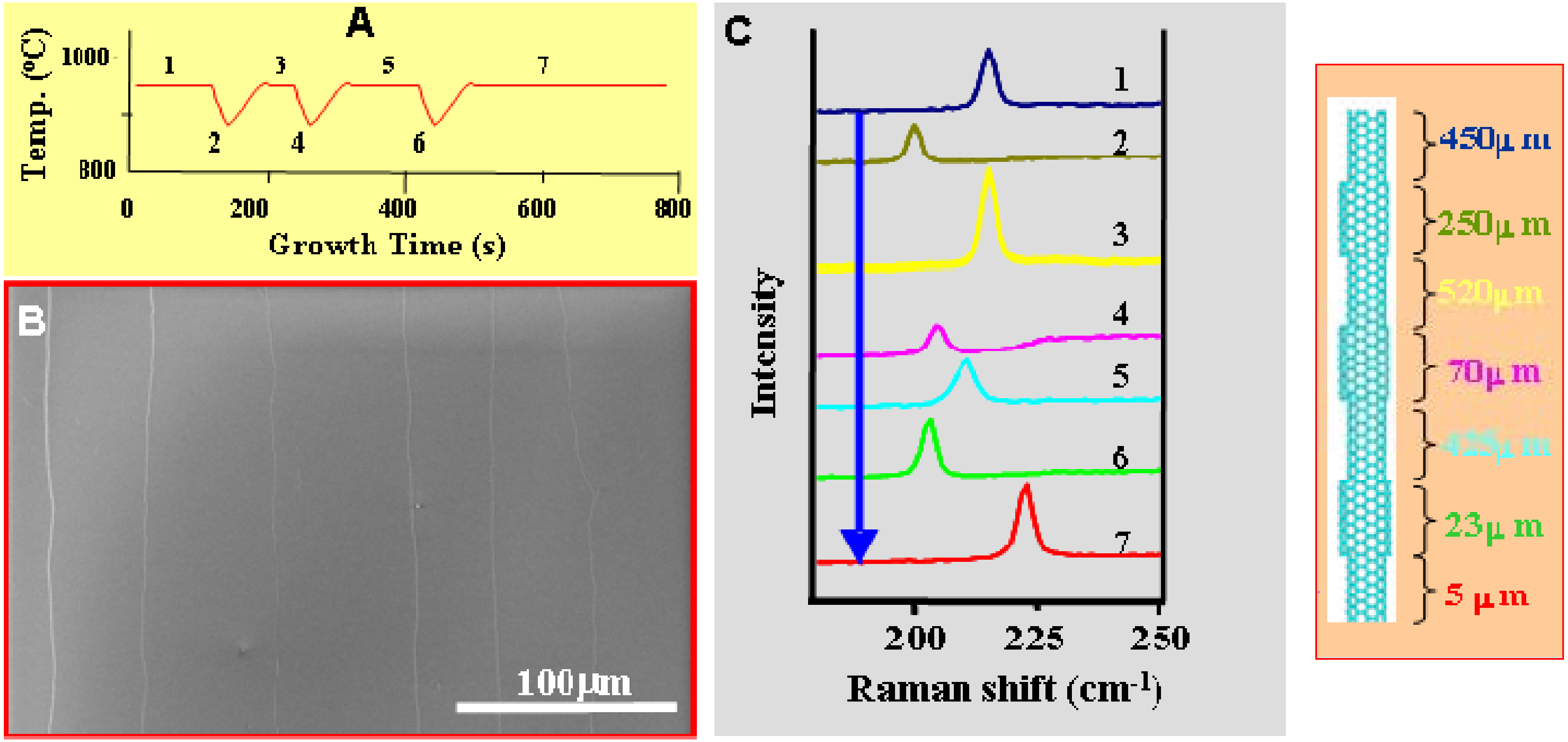
Tube Diameter from Wide to Narrow Distribution

Narrowing the distribution of tube diameters by sequential temperature step-up or step-down



J. Zhang et. al., J. Phys. Chem. C, 2009, 113(30),13051-13059

Multiple Intratube Nanojunctions by Repeating Temp. Oscillation



Six intramolecular junctions were induced by three temperature oscillations between 950°C and 880°C during CVD. (A) shows the scheme of temperature oscillation with time; (B) is an SEM image of several parallel ultralong SWNTs grown during the temperature oscillation; (C) shows Raman RBM peak positions along a SWNT, each peak corresponds to a time period in (A).

J. Zhang et. al., Nature Materials, 2007, 6, 283

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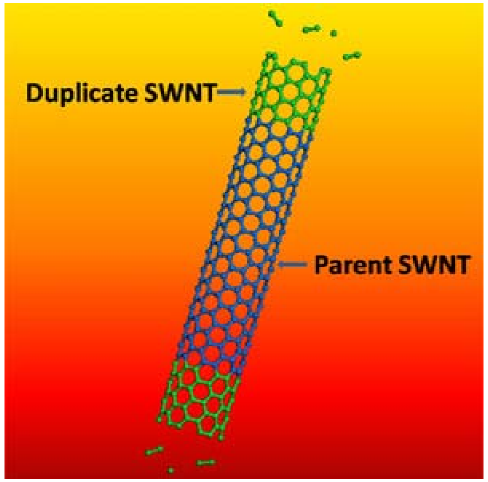
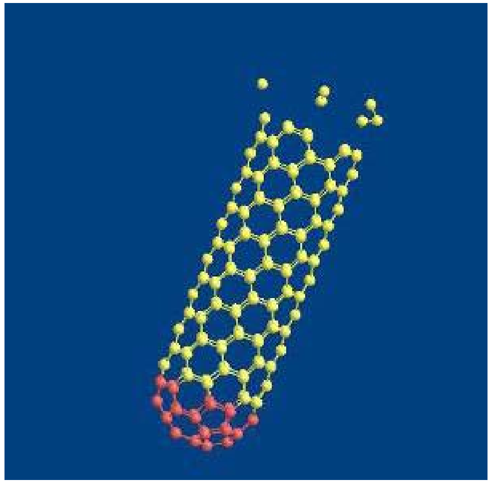
But carbon nanotubes could, in the future, provide more than just thermal management, they could form the basis of electronic devices themselves. To realize such a goal, it will be necessary to find a means of creating intramolecular junctions in a controlled manner. Researchers from Peking University, China and Los Alamos National Laboratory claim to be able to form single-walled carbon nanotube (SWNT) intramolecular junctions simply by varying growth temperature [Yao *et al*., *Nat. Mater.* (2007) **6**, 293].

It is currently accepted that the size of the catalytic particle used to grow a nanotube determines its diameter. However, the Chinese researchers observe that the diameter of a SWNT varies with growth temperature during catalytic CVD, even with the same catalytic particle. The results show that if the growth temperature is increased from 900°C to 950°C, the diameter of the SWNT decreases by ~4%. Conversely, when the growth temperature is decreased, the SWNT diameter increases. With the change in nanotube diameter comes a change in chirality and, hence, bandgap. However, if the growth temperature is held constant, the researchers observe nanotubes of uniform diameter.

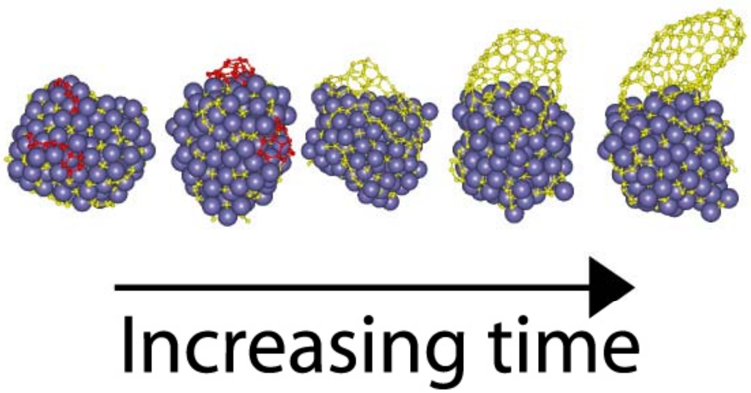
"These strategies provide a potential approach to grow SWNT intramolecular junctions at desired locations, sizes, and orientation," says Jin Zhang of Peking University. If such a simple method could reliably produce SWNT intramolecular junctions, it could be a significant step toward next-generation, carbon-nanotube-based electronic circuits and devices.



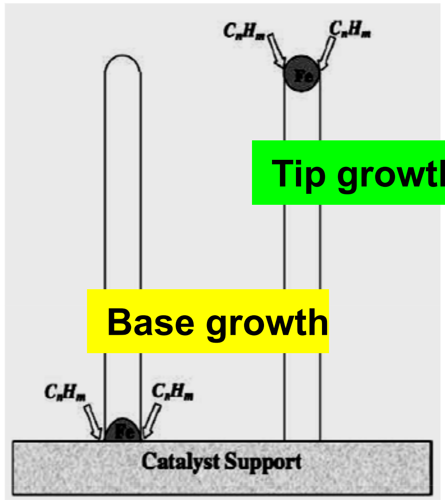


Cap-engineering for Growing SWNT with Controlled Chiralities

Growth Mechanism of SWNT



www.adm.hb.se/~KIB/nanotubes.htm



1. Cap formation on catalyst

2. Carbon atoms bound to the cap and form a SWNT

The cap structure determines the structure of the formed SWNT.

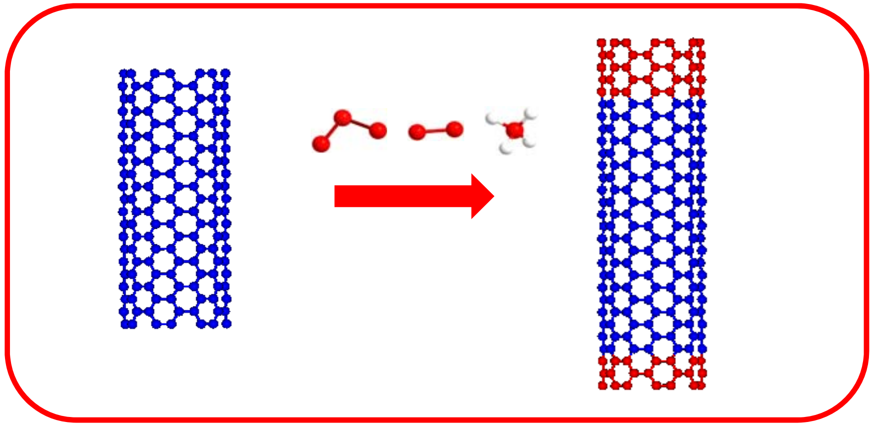
However, it is hard to control the cap structure by controlling the structure of catalyst nanoparticles.

It follows the Vapor – Liquid – Solid (VLS) Mechanism

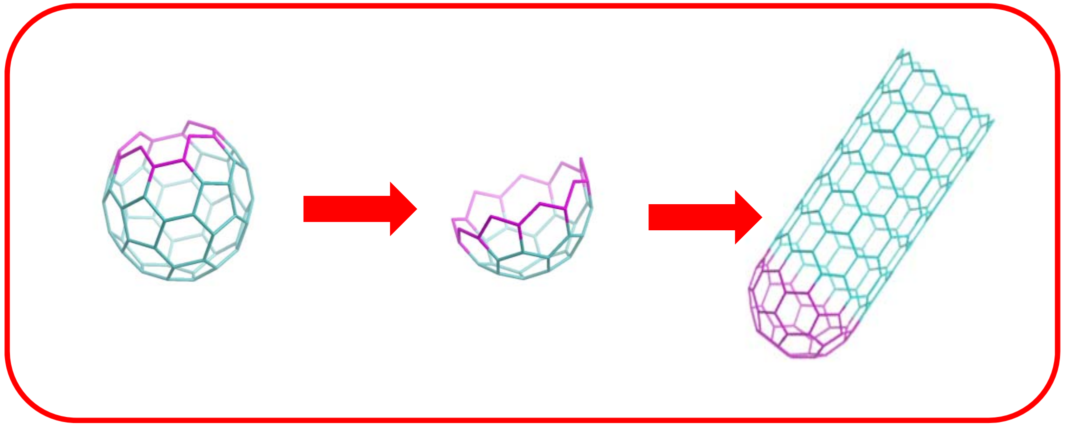
Our Strategies ------ Cap-engineering

Based on the concept of SWNTs Cloning, using a open end SWNT or opened C_{60} as seed/cap to grow SWNT. The structure of the open end SWNT or opened C_{60} determines the structure of the formed SWNT.

Open-end SWNT as seed/cap

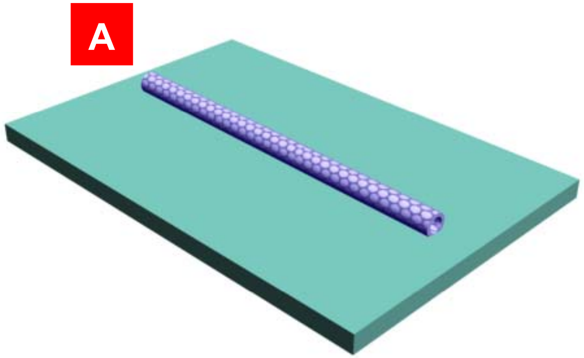


Opened C_{60} as seed/cap

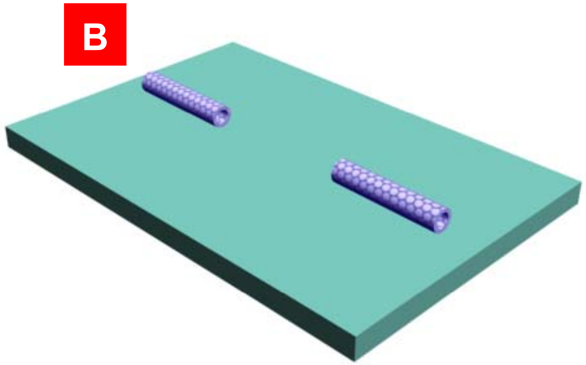


Vapor-Solid Growth Mechanism / Open-End Growth Mechanism

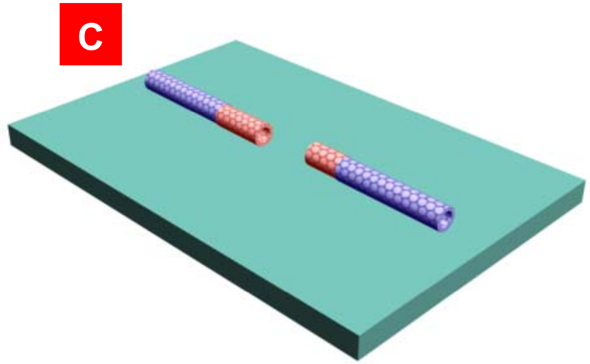
Our experimental scheme



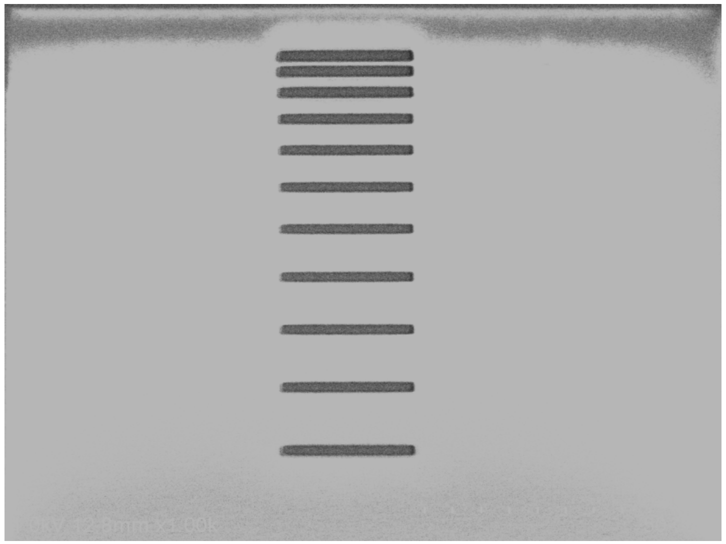
Original “seed” catalyst

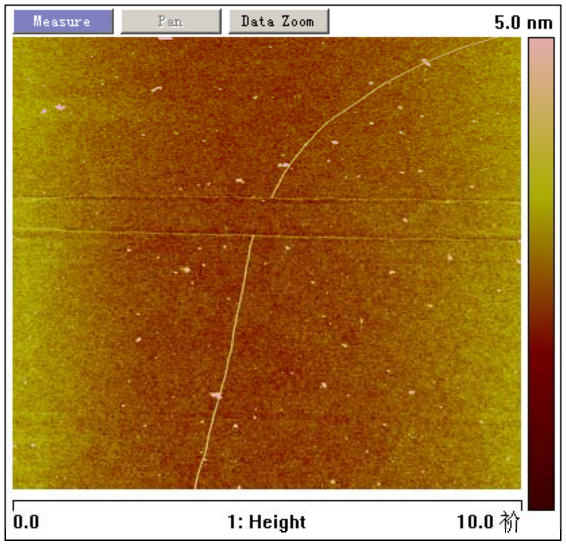


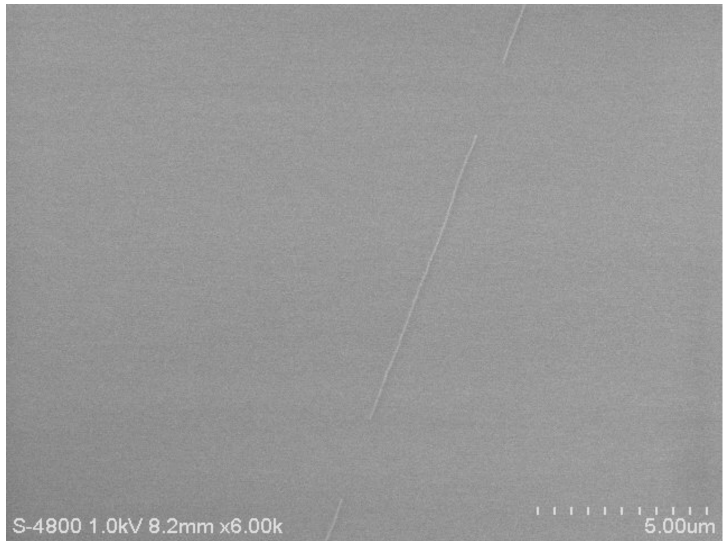
EBL+O_2 plasma



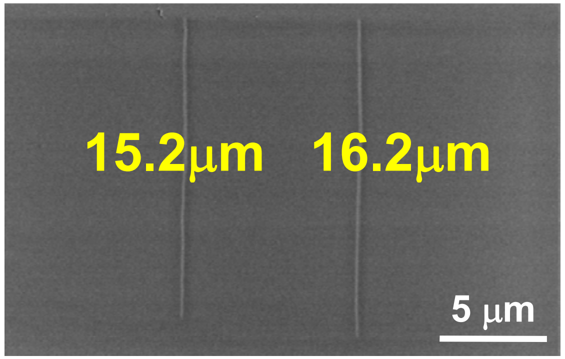
Second growth

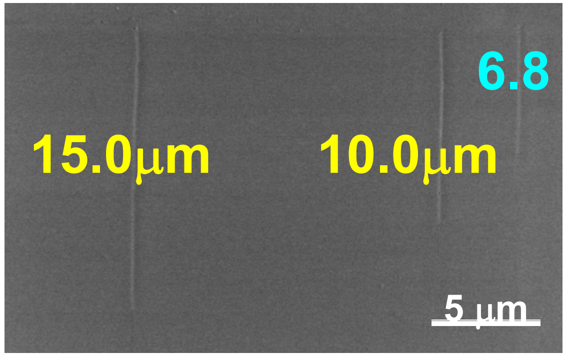


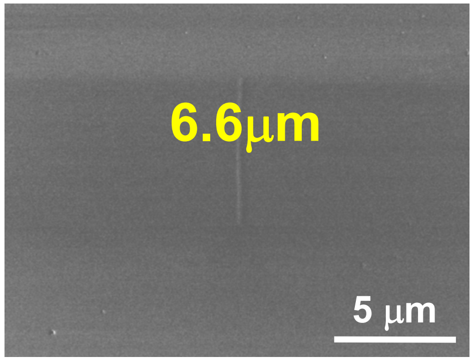




Cloning SWNTs on Quartz Surface





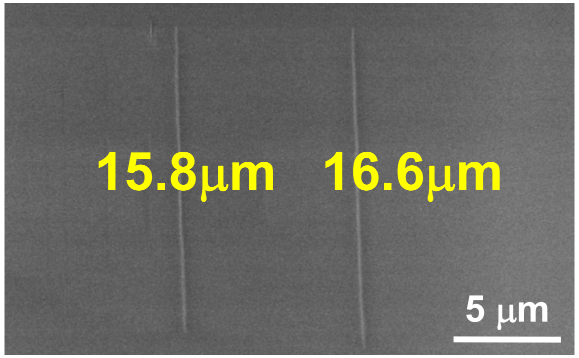


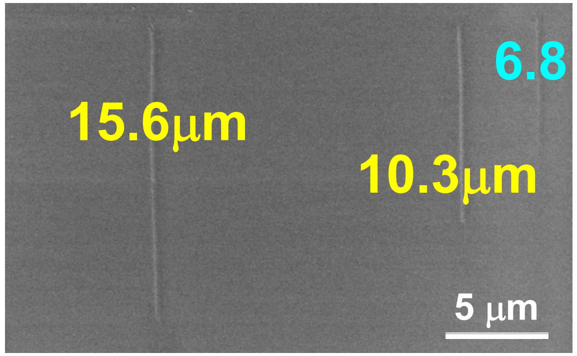
Tube length increase:

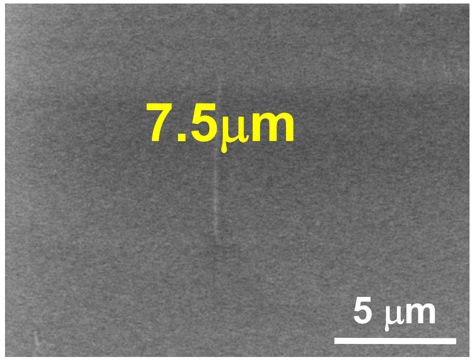
0 μm – 1μm

Rate of success for cloning:

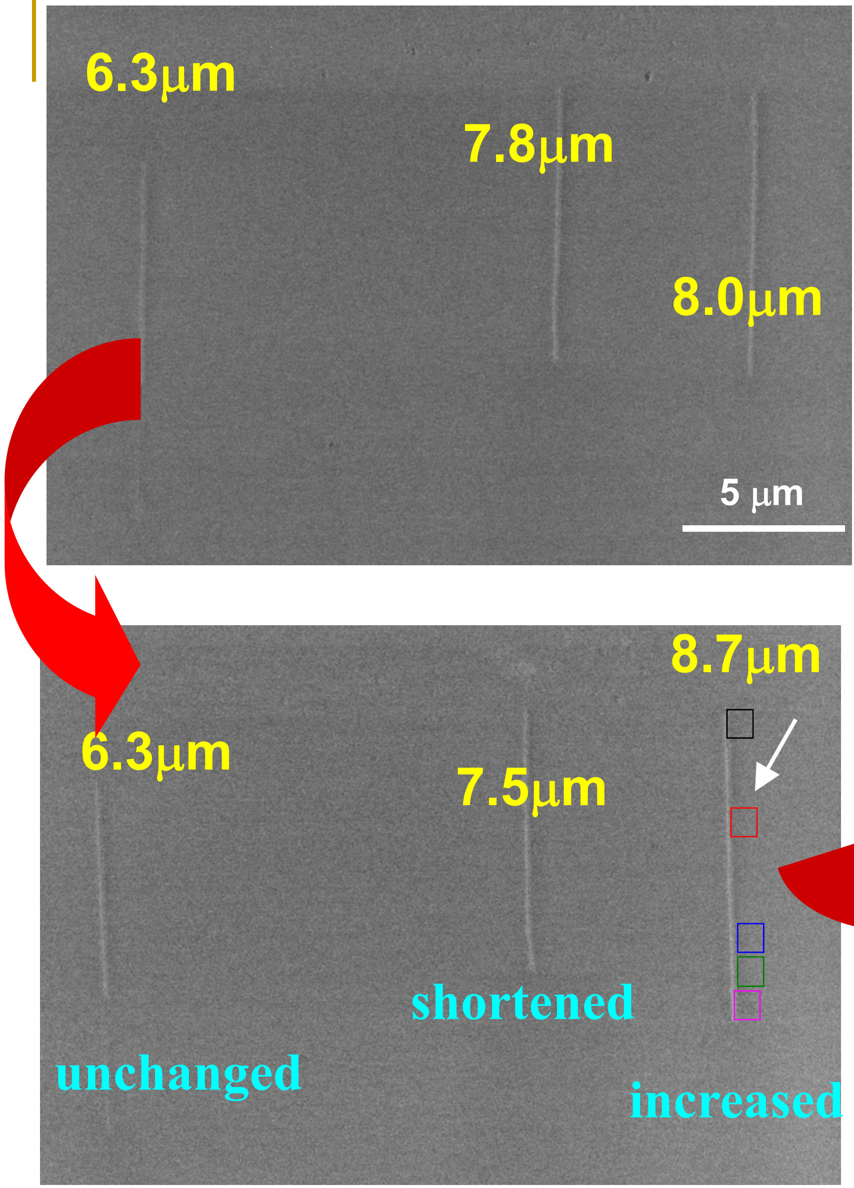
24/59 = 40.7%

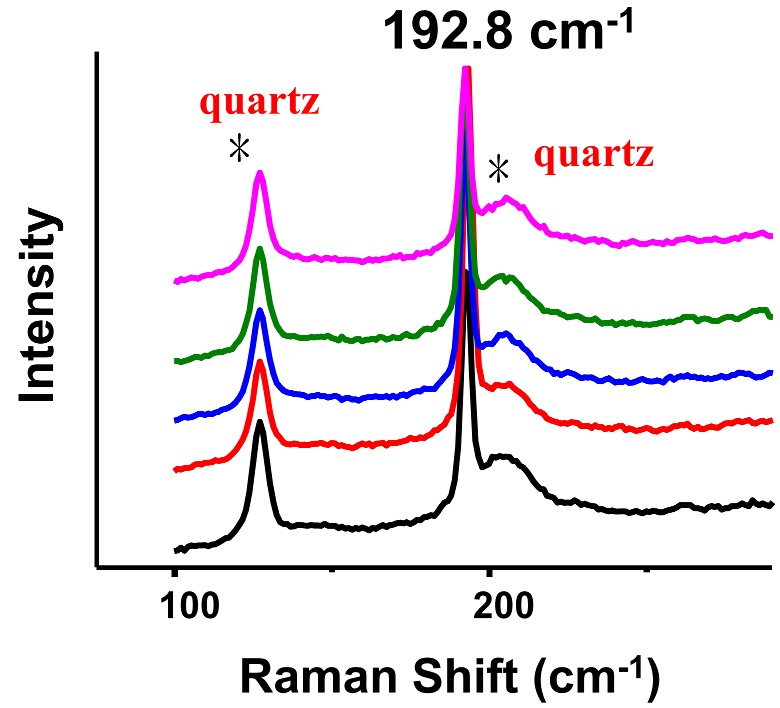






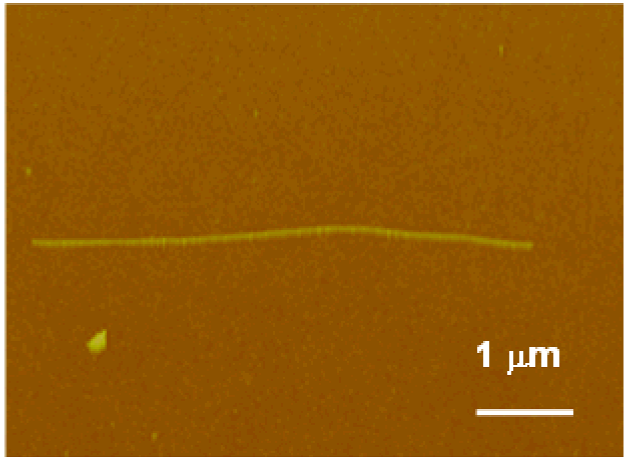
Before growth | **After growth**

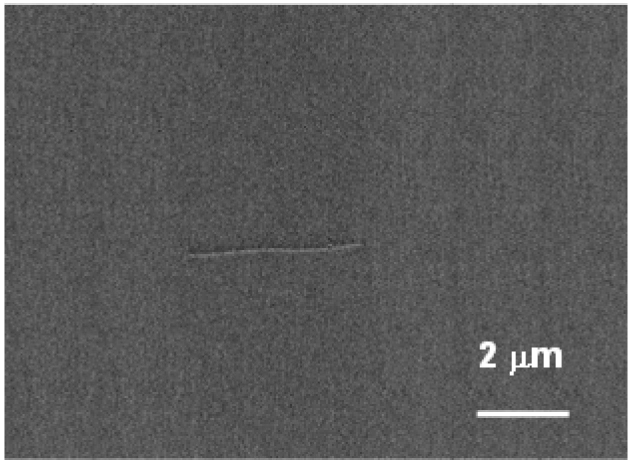




Tube diameter & chirality keep unchanged after cloning growth

Cloning SWNTs on SiO_2/Si Surface





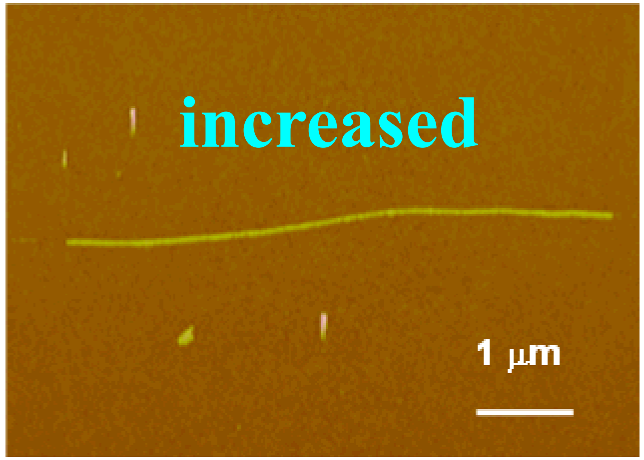
Tube length increase:

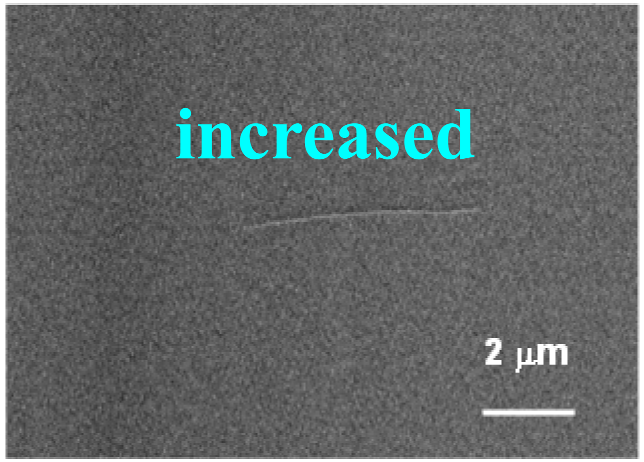
0 μm – 4.6 μm

Rate of success for cloning:

56/600 = 9.3%

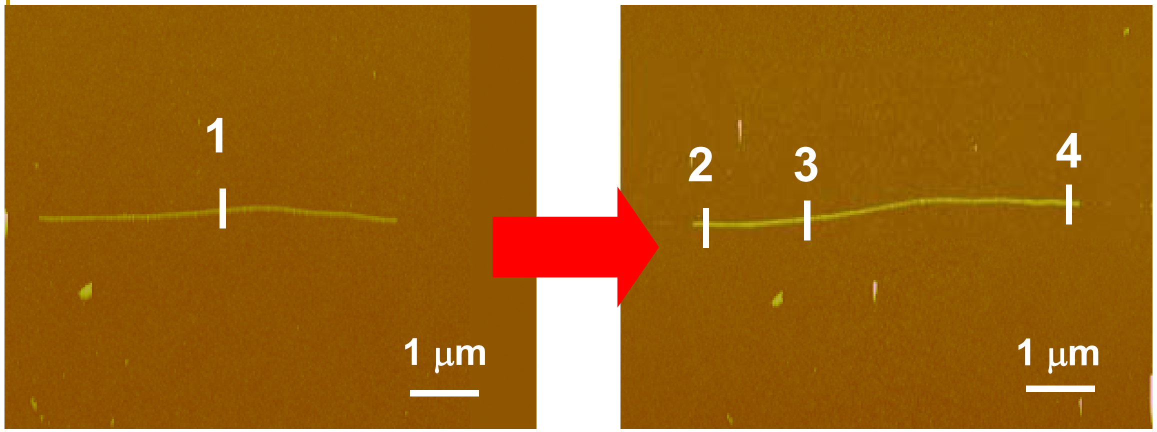
- ***$CH_4/C_2H_4/H_2$=100/5/300***
- ***Growth T=975^{o}C for 15min***

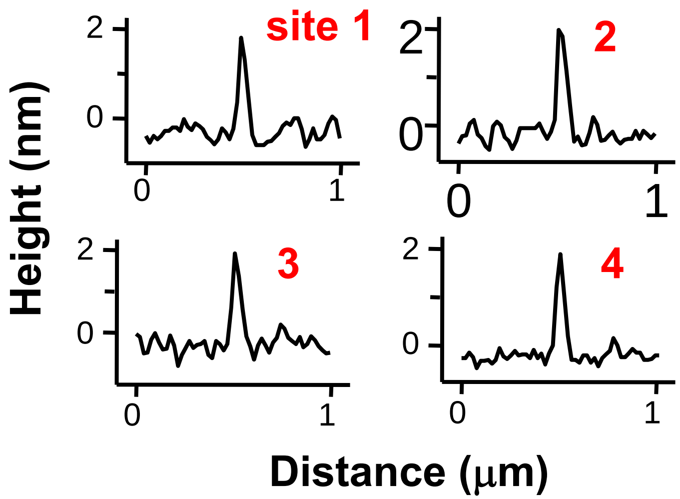




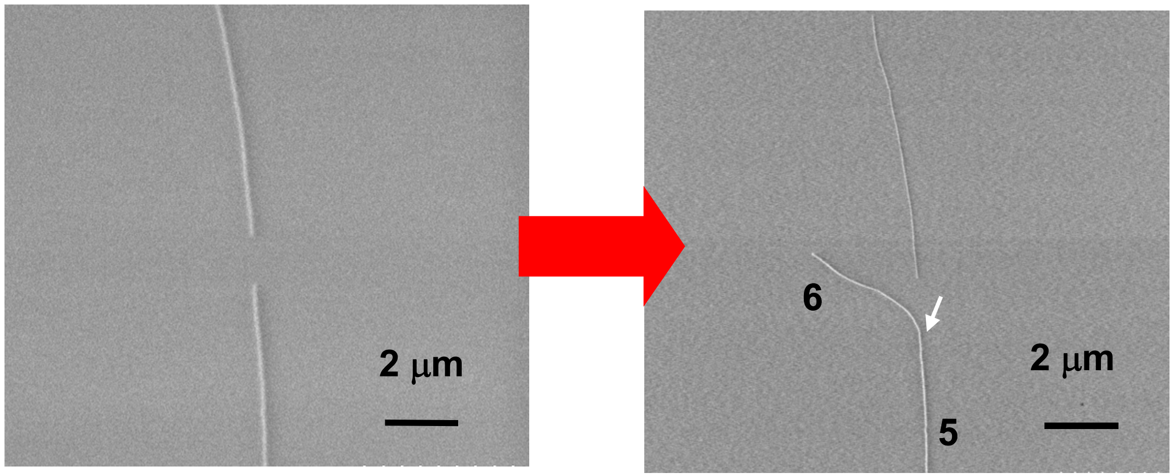
Before growth

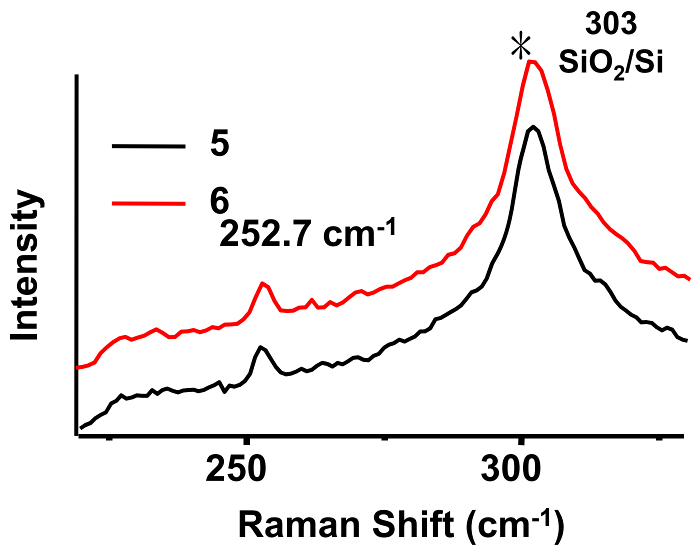
After growth





Before growth **After growth**

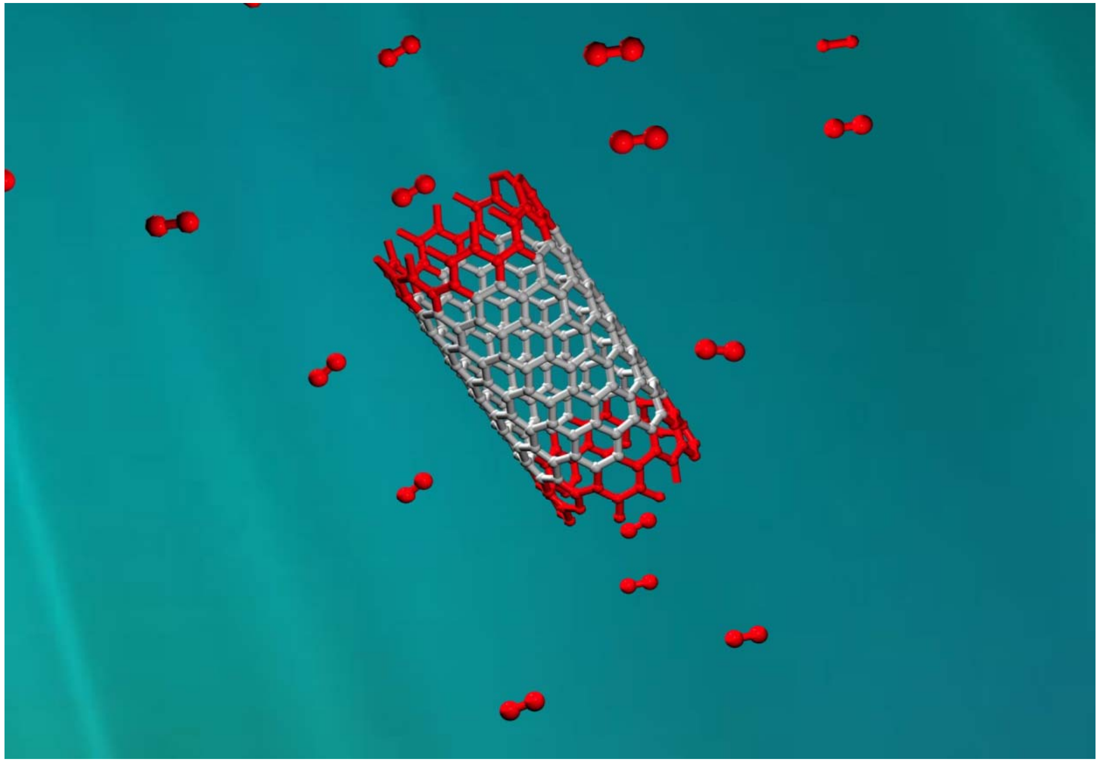


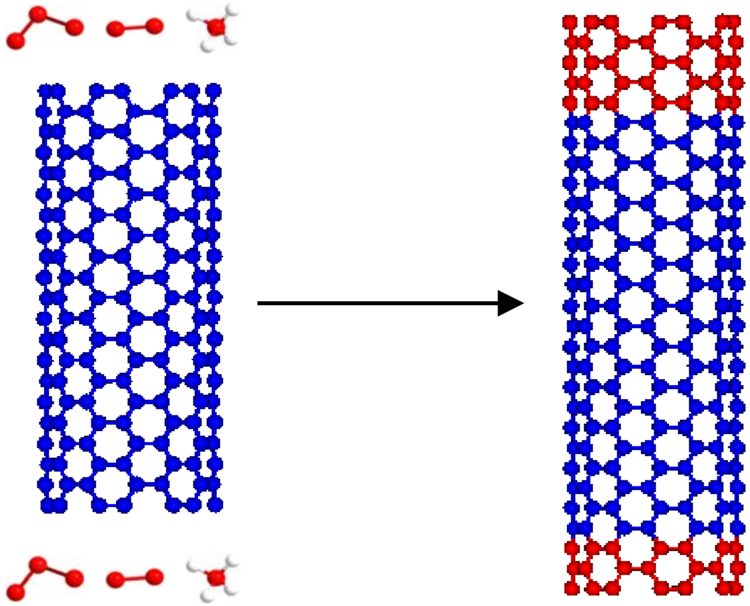


AFM and Raman evidence for the diameter & chirality maintenance

J. Zhang et al., Nano Lett., 2009, 9, 1673

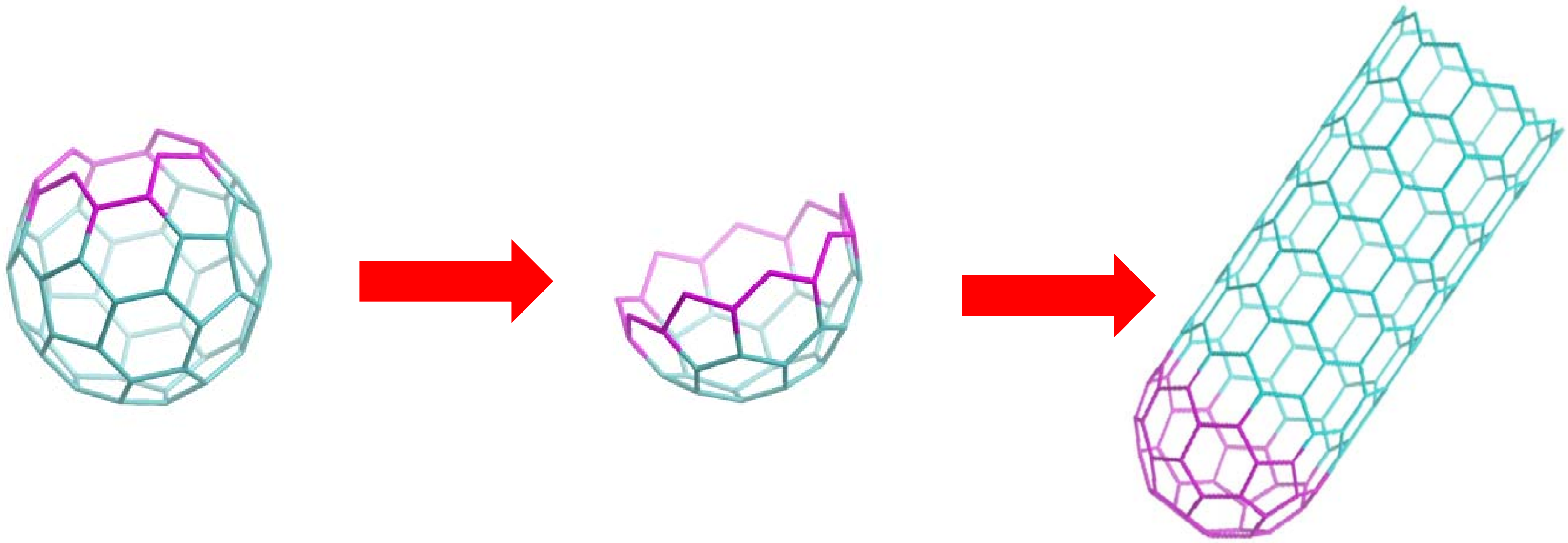
Open-End Growth Mechanism



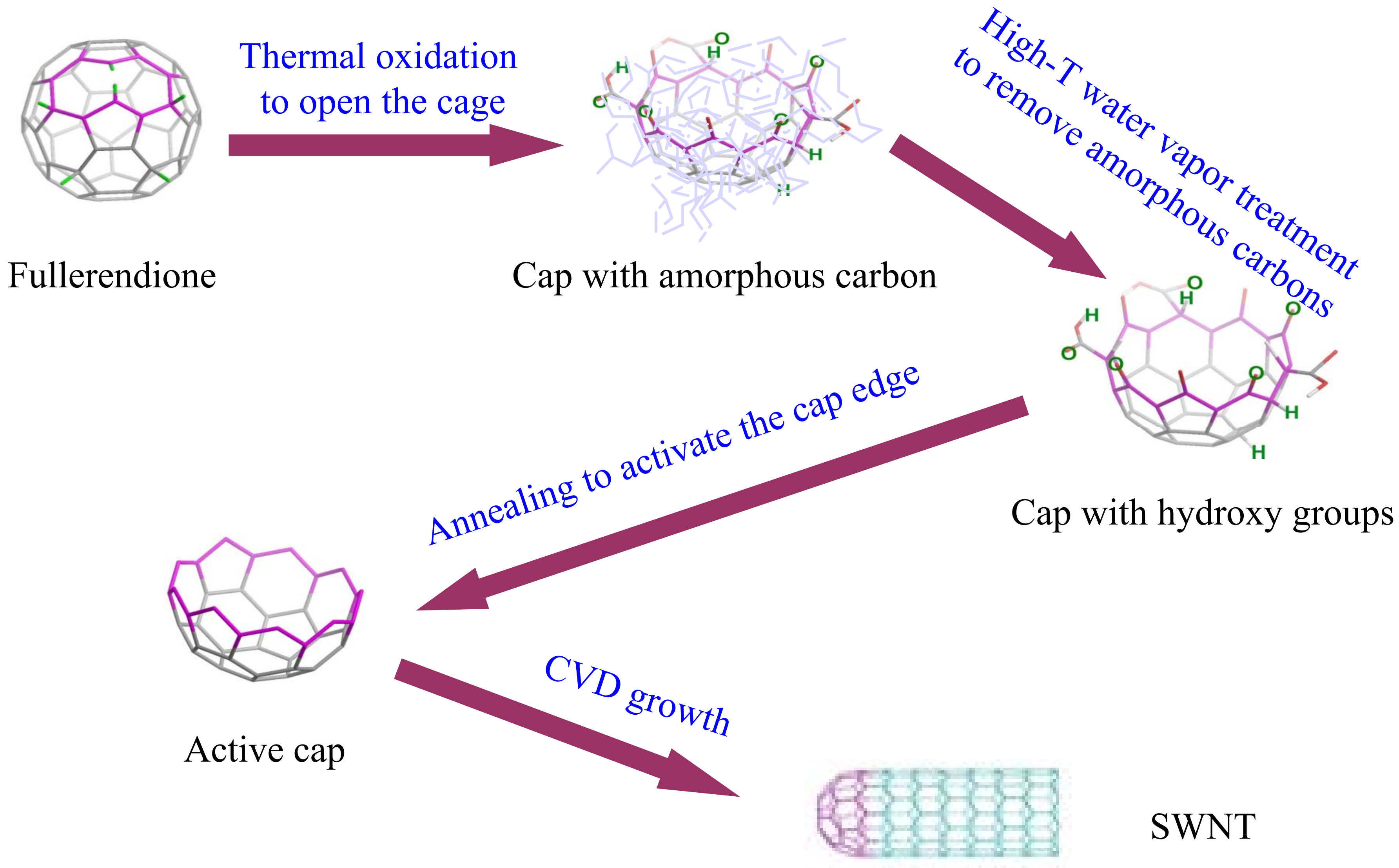


“VS” growth model ?

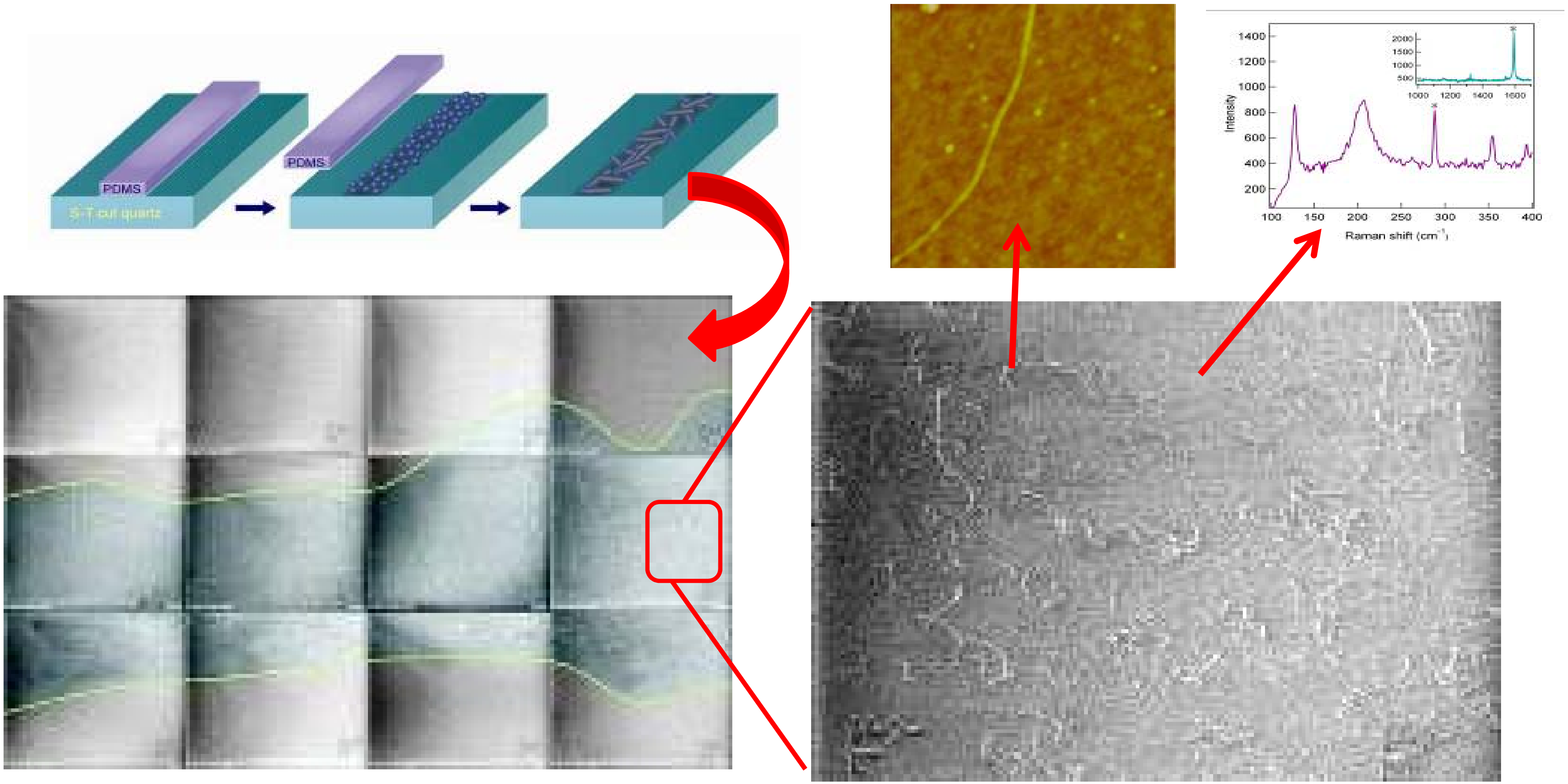
Using C_{60} cap to grow SWNTs



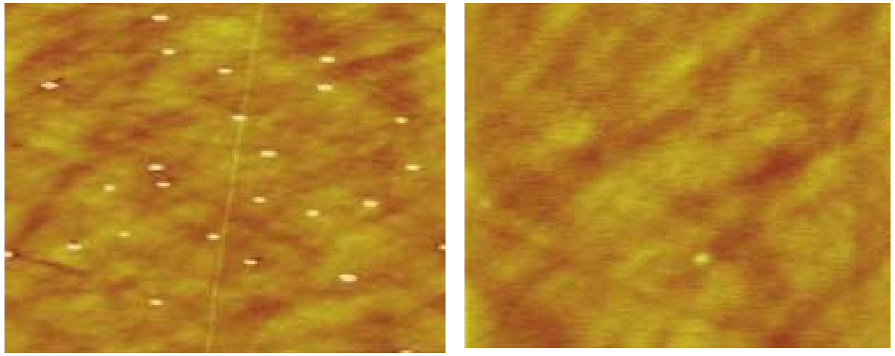
Experiments



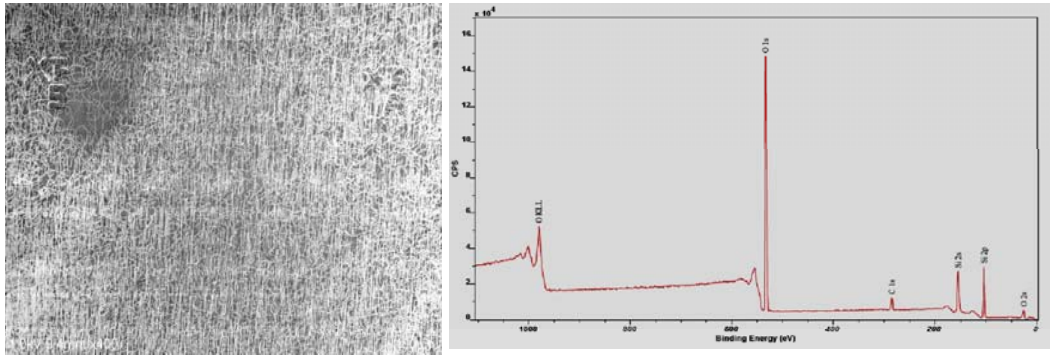
Growing SWNTs Using Opened C_{60} as Seeds: Growth Result



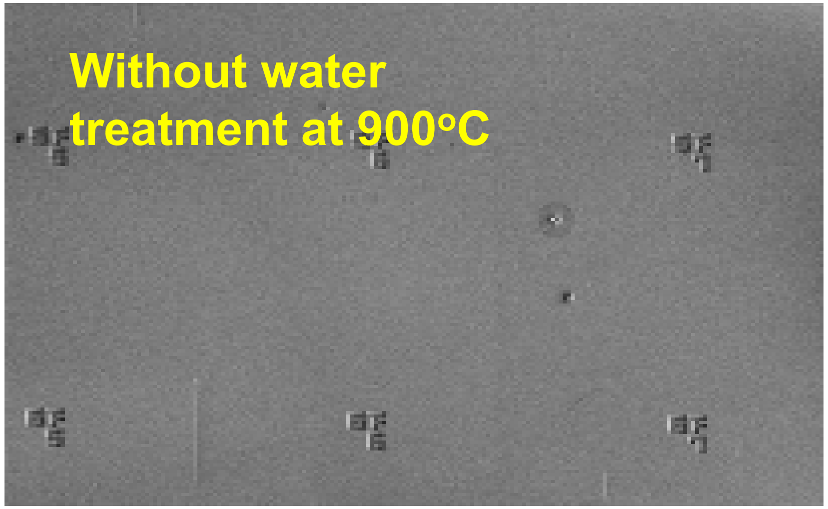
Evidence of SWNTs Grown from Opened C_{60}

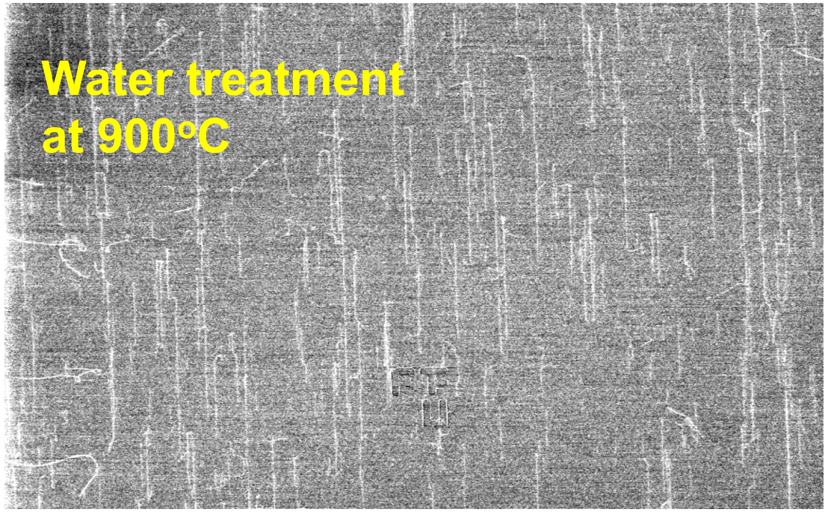


Morphological a SWNTgrown from opened C_{60} and after heat treatment



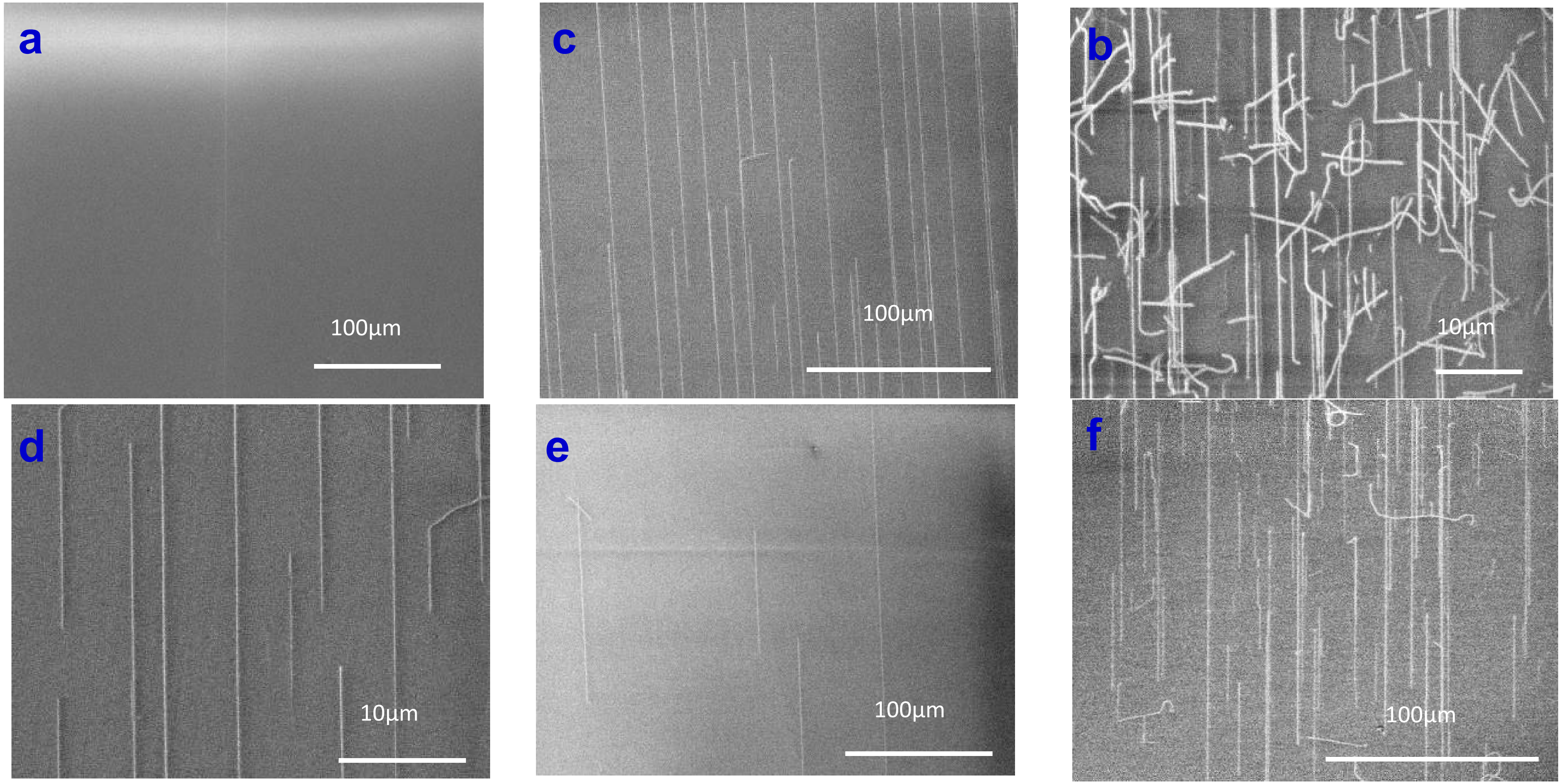
SEM image of a SWNT grown from opened C_{60} and XPS of the SWNTs sample





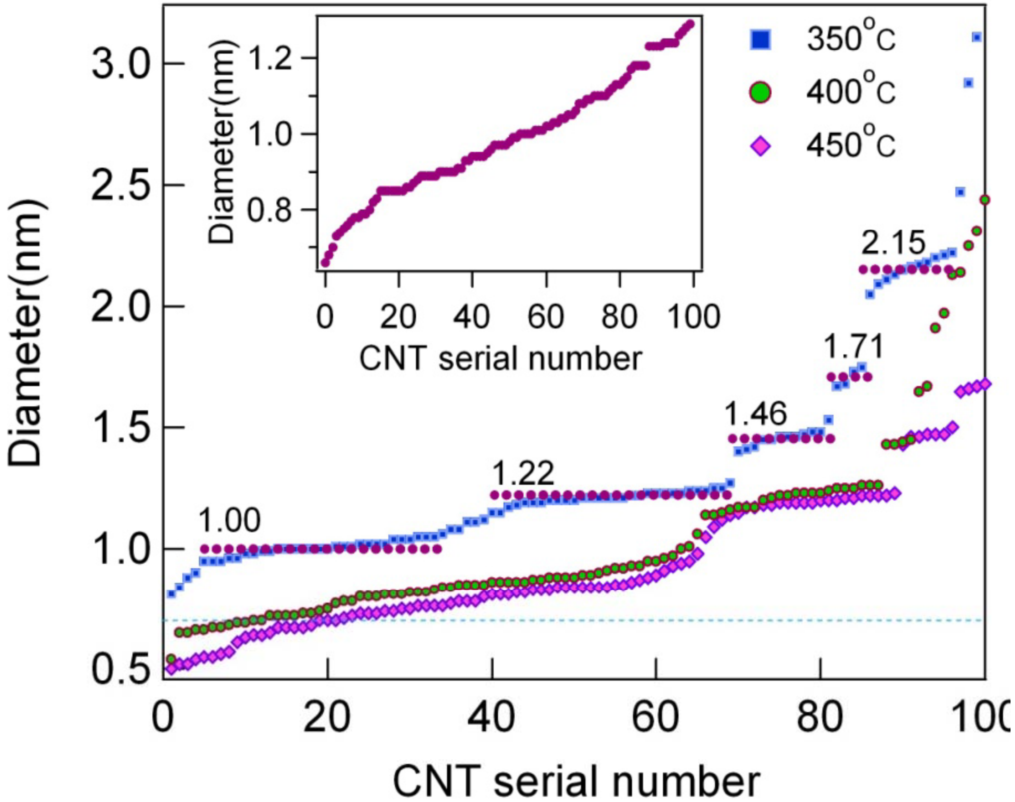
Water treatment is very important for SWNTs growth!

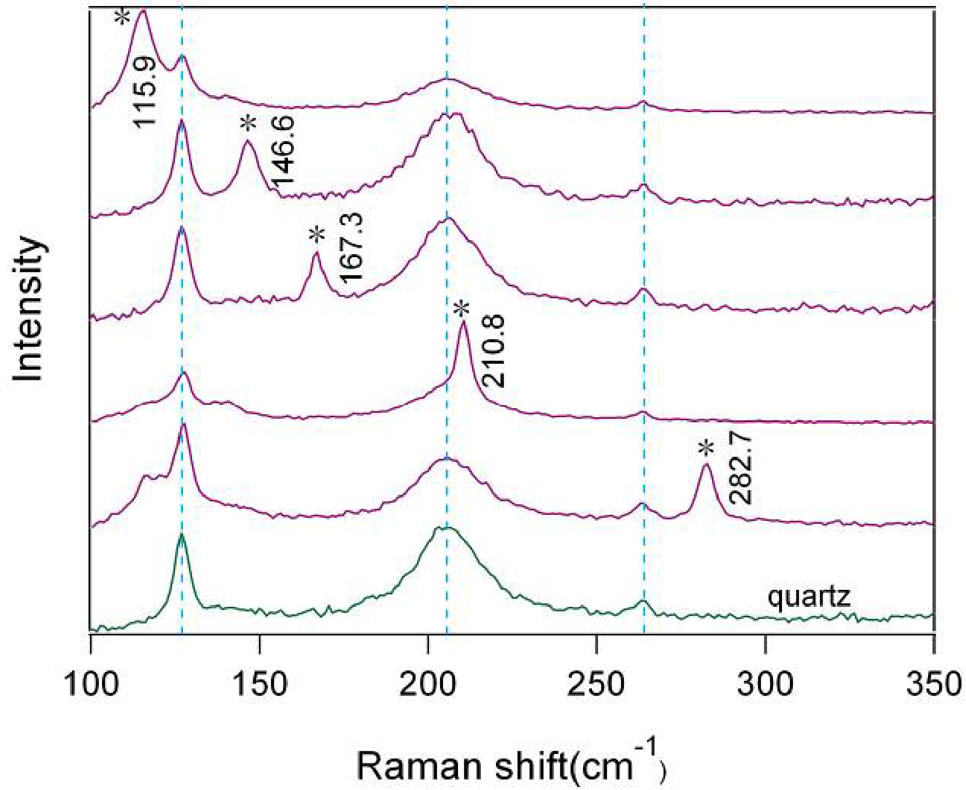
Different thermal oxidation temperature



(a)-(e) SWNTs grown from fullerendione using thermal oxidation temperatures of 300, 350, 400, 450 and 500 °C respectively. (f) SWNTs grown from pristine C_{60} using an oxidation temperature of 500 °C

Diameter Distribution of SWNTs grown by using Opened C_{60} caps

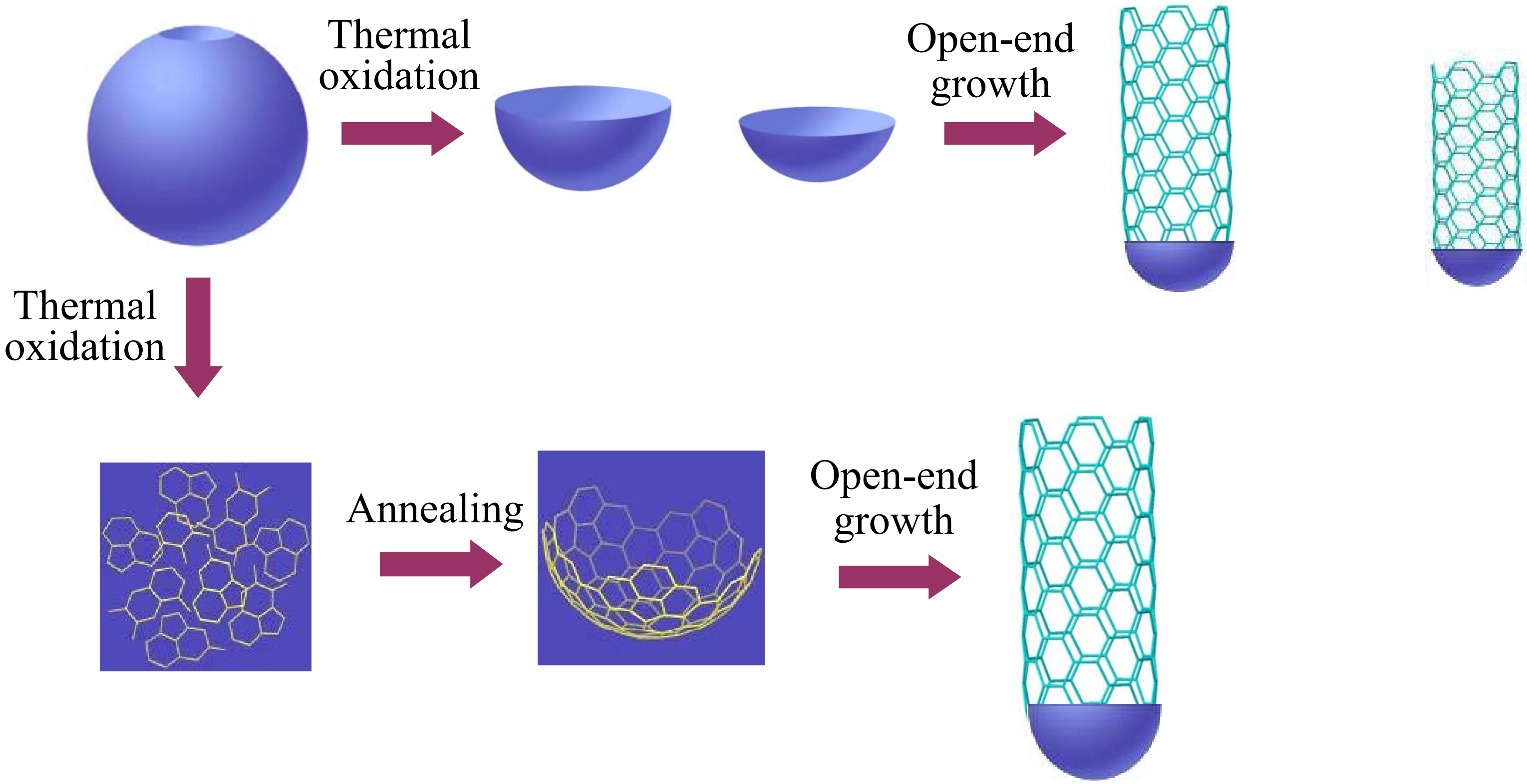




Diameter distribution of SWNTs grown from fullerendione under different oxidation conditions (measured from AFM).

J. Zhang et al., Nano Lett., 2010, 10, 3343

Possible Growth Mechanism



The caps from C_{60} has a discreet diameter distribution.

The formed SWNTs are expected to have a discreet diameter distribution.

featured highlight

Carbon nanotubes: Perfect clones

Published online 29 June 2009

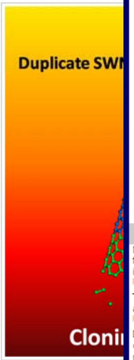


Fig. 1: Using
nanotubes (SWN
growth process m
co

Although methods for producing single-walled carbon nanotubes have advanced considerably in recent years, growing nanotubes with specific structures remains difficult. Nanotubes can be semiconducting or metallic in character depending on the orientation of carbon hexagons within the structure, and controlling this behavior is crucial for future nanoscale electronic applications.

Now, Jin Zhang and colleagues[1] from Peking University in China have devised a novel method for the growth of single-walled carbon nanotubes that allows precise control of the nanotube properties. Using seeds cut from existing nanotubes, the researchers grew new extensions that retained the original structure — perfect 'clones' of the parent segments (Fig. 1).

Working with ultralong single-walled carbon nanotubes grown by chemical vapor deposition, Zhang's group first covered the nanotubes with a lithographic mask. Then, using electron-beam lithography and oxygen plasma ion etching, the researchers prepared short, open-ended segments of the nanotubes as seeds. These small sections were th remove any impurities.

To grow new nanotube extensions, a stream of gas containing carb over the seed segments. Using atomic force and scanning electron team observed new growth of several micrometers in length exten Raman spectroscopy confirmed that the newly grown nanotube se original seed structure.

According to Zhang, growing the nanotube clones required accurate a mixture of acetylene and methane gases. "We used acetylene to decomposition of methane gas into carbon radicals. If we didn't use growth temperature was below 945 °C, no amplified growth occur

Instead of requiring an external additive, the growth mechanism dis the open ends of the nanotubes themselves as catalysts. The seed the nanotube structure, and any new growth via carbon radicals re

The researchers reported that, on a quartz substrate, over 40% of produced new cloned segments. "We think if the open-ended segm the growth efficiency would be greatly improved," says Zhang.

Zhang and colleagues are now undertaking large-scale growth trials carbon nanotube clones.

Reference

1. Yao, Y.,[1] Feng, C.,[1] Zhang, J.[1]* & Liu, Z.[1] "Cloning" of single-walled car growth mechanism. *Nano Lett.* **9**, 1673–1677 (2009). | article |

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Most Recent Spotlights

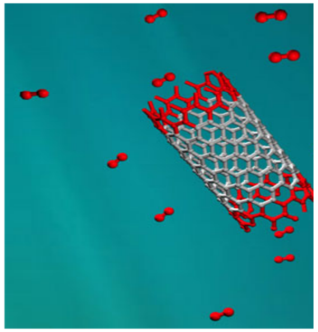
Posted: April 3, 2009

'Cloning' might solve the chirality control issue

(*Nanowerk Spotlight*) Notwithstanding the tremendous amount of carbon nanotubes, the synthesis of single-walled carbon nanotub still has not been achieved. Current production methods for carbo different diameter, length, chirality and electronic properties, all pa blended with some amount of amorphous carbon. The separation properties remains a technical challenge. Especially SWCNT sor composition and chemical properties of SWCNTs of different type conventional separation techniques inefficient.

Using the concept of cloning, scientists in China have discovered special (n, m) indices SWCNTs.

"We found that an open-end single-walled carbon nanotube, which grown via an open-end growth mechanism," Jin Zhang tells Nanow the parent tubes – the 'seeds' – have the same chirality."



Schematic illustration of a single walled carbon nanotube clone. (
Laboratory for Molecular Scien

These findings by Zhang, a professor of chemistry and molecular Laboratory for Molecular Sciences, and his colleagues Zhongfan L be not only helpful to understand the formation mechanism of sing turn the controllable growth of SWCNT with identical chirality into

Moreover, this growth mechanism might be an effective way for cl sheets. Furthermore, large scale cloning of single chirality SWCN

The scientists reported their findings in the March 13, 2009 online Single-Walled Carbon Nanotubes via Open-End Growth Mechanis

For their technique, Zhang's team first grew ultralong (several tens substrate. The nanotube length is only limited by the substrate si the growth time. Then, the ultralong SWCNTs were cut into short lithography (EBL), oxygen plasma ion etching, and lift-off, which c and the stencil in the second growth.

In a third step, the SWCNT 'clones' were grown from the open-enc end seeds in a chemical vapor deposition (CVD) furnace to first g functionalized SWCNTs, which could help expose the active oper and C_2H_4 carbon source.

"The cloned nanotubes usually grew as much as a few micromete amplified growth was 4.6 µm" says Zhang. "We thought that if the the substrate such as the open-end SWCNTs are suspending, th

While this strategy works in principle, the growth efficiency of clo mechanism are problems which still need to be solved.

"We have measured more than 600 short seed segments and fou around 9%" says Zhang. "This yield can be greatly improved up t substrate."

The key point of SWCNT cloning is to verify the duplicate SWCNT parent SWCNTs. Through atomic force microscopy and micro res characterization the team determined that the parent nanotube ar same structure.

According to Zhang, the open-end SWCNT catalyst (seed) is mor catalysts for the growth of SWCNTs.

"Firstly, it can not congregate at high growth temperate. The meta congregate at high temperature which will widen the diameter of S carbon radicals will directly add to the open-end and thus the chir the same structure as the parent SWCNTs. Thirdly, our results su structures might act as a template for the formation of SWCNTs."

By Michael Berger. Copyright 2009 Nanowerk LLC

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research highlight

Published online 0000-00-00 00:00:00

Carbon nanotubes: Capped for growth

High-temperature oxidation reactions open fullerenes to seed carbon nanotube growth.

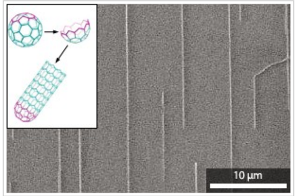

Fig. 1: Schematic representation of the growth of a single-walled carbon nanotube from an opened fullerene cap (inset), and a scanning electron microscopy image of the prepared nanotubes.

From Ref. 1. Reproduced with permission. © 2010 ACS

Single-walled carbon nanotubes (SWNTs) are poised to play central roles in future nanoelectronic devices, but it remains necessary to develop methods to reliably control their structures. Even small changes in the width of the tubes or the orientation of carbon atoms can alter the conductivity of SWNTs, determining whether they behave as a semiconductor or metal. Now, in a collaboration between Peking University in China and the Samsung Advanced Institute of Technology in Korea, Jin Zhang, Jae-Young Choi, Zhongfan Liu and co-workers[1] have developed a 'cap engineering' method that generates SWNTs with well-defined diameters.

Typical SWNT syntheses rely on the formation of hemispherical carbon-based nanostructures, or 'caps', on metal nanoparticle catalysts at high temperature. These caps initiate the growth of nanotubes, and also define their final structure. The extreme conditions required for synthesis, however, make it difficult to generate caps of uniform size. "We think that if the SWNTs can be grown from existing carbon caps through a vapor – solid or open-ended growth mechanism, the structure of SWNTs could be controlled," says Zhang.

The team developed a method using fullerenes (C_{60}) and derivatives called fullerendiones, which can open to form caps with predetermined diameter. After depositing these ball-shaped carbon structures on a quartz substrate, the team cracked opened the carbon – carbon bonds by high-temperature oxidation. Treating the caps with water eliminated any amorphous carbon from the structure, and subsequent heating removed oxygen-containing groups. The activated caps were finally exposed to ethanol at 900 ° C, which induced the growth of uniform SWNTs (Fig. 1). Ethanol releases carbon radicals that are added directly to the cap ends, resulting in the growth of nanotubes by an open-ended growth mechanism.

The researchers found that the oxidation temperature was crucial in determining the diameter of the fullerene-derived caps, and therefore for controlling the SWNT structure. Higher temperatures caused the breakage of more carbon – carbon bonds, giving smaller caps and resulting in thinner SWNTs. The team also observed that at lower temperatures, the oxidation produced oxygen-bridged 'opened fullerenes' that further coalesced into larger caps, leading to larger-diameter nanotubes.

"We are now working on controlling the chirality of SWNTs during growth using this cap engineering approach," says Liu.

Reference

1. Yu, X.,[1] Zhang, J.,[1]* Choi, W.M.,[2] Choi, J.-Y.,[2] Kim, J.M.,[2] Gan, L.[1] & Liu, Z.[1]* Cap formation engineering: from opened C_{60} to single-walled carbon nanotubes. *Nano Lett.* **10**, 3343 (2010). | article |

Author affiliation

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Summary

Single-Walled Carbon Nanotubes

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Application the SWNTs in Future Devices

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Growing SWNTs on Surface
with Controlled Structures

Although it is still difficult to make a precise control of the diameter, chirality and local band structure of single-walled carbon nanotubes, there exists a big space for further efforts.

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Prof. Jing Kong	MIT
Prof. Mildred Dresselhaus	MIT

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MOST(2006CB932701)


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Welcome to Beijing!