Structure Controlled Growth of Single-walled Carbon Nanotubes on Surface

Jin ZHANG (   )

Beijing National Laboratory for Molecular Sciences(BNLMS)
College of Chemistry and Molecular Engineering
Peking University, Beijing 100871, P. R. CHINA
Email: jinzhang@pku.edu.cn

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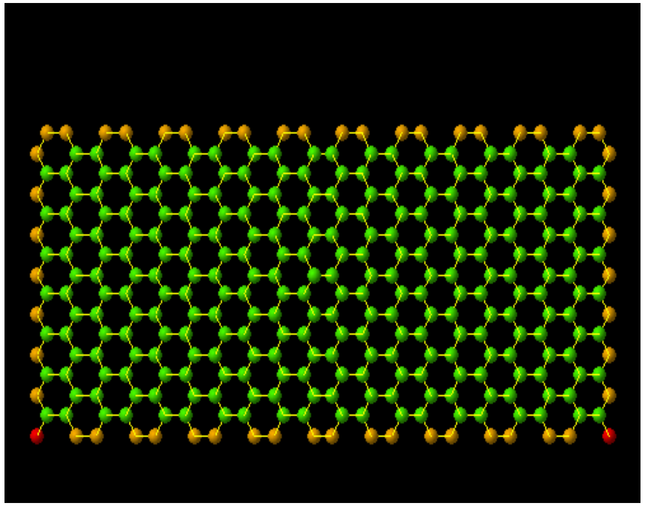
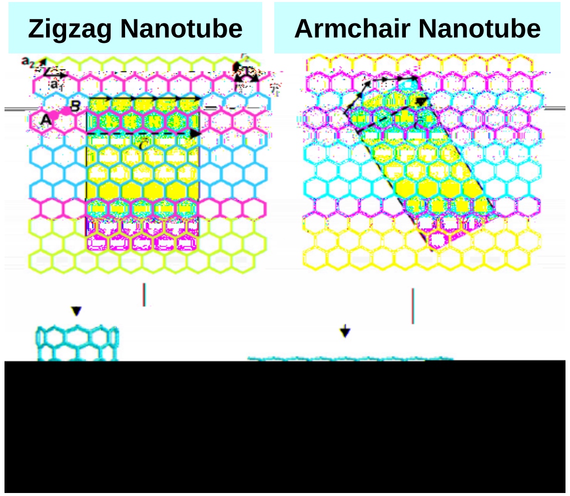
Introduction of Single-walled Carbon Nanotubes



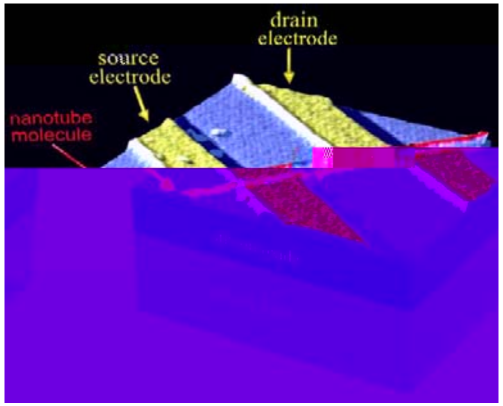


$$C_h = na_1 + ma_2 \equiv (n,m)$$

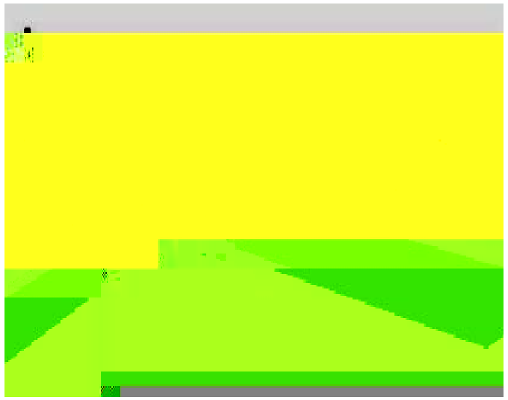
$$d_t = \sqrt{3}a_{C-C}(n^2+m^2+nm)^{1/2}/\pi$$

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

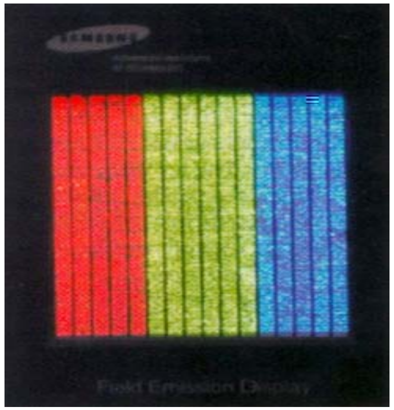
$$n-m = \begin{cases} 3p & \text{metal} \\ 3p \pm 1 & \text{semiconductor} \end{cases}$$



Nanotube transistor



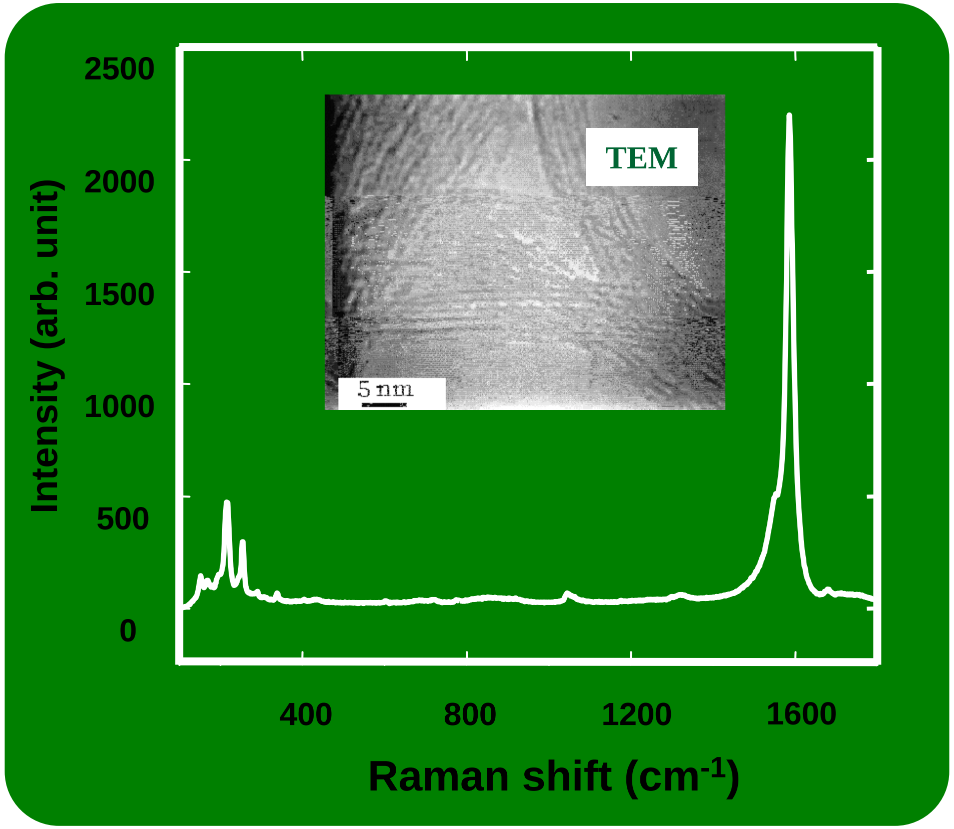
Nanotube RAM

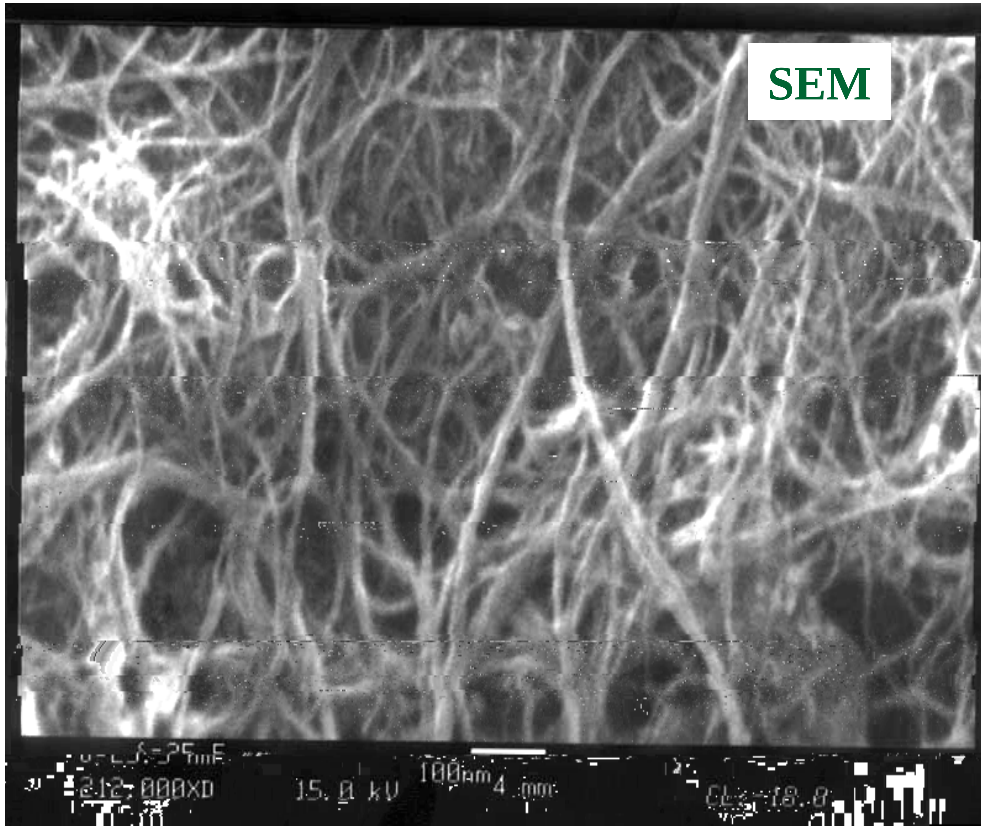


Flat panel display

Nanotube interconnect

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



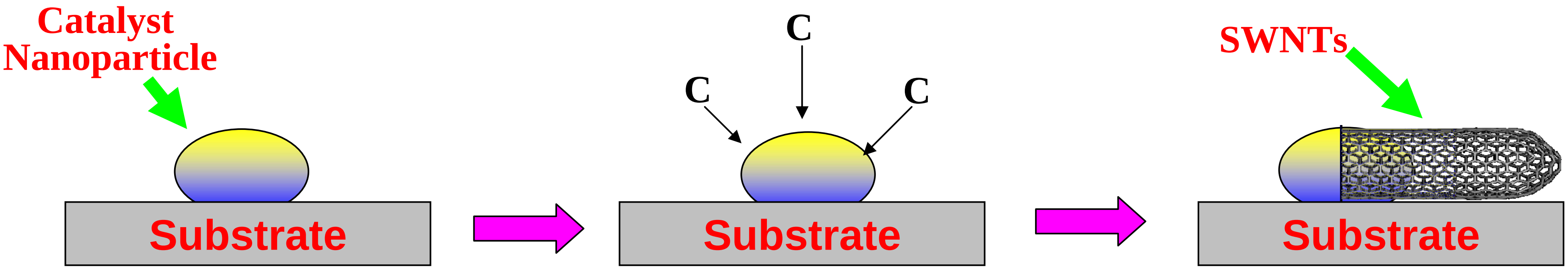


Support: MgO; Catalysts: Fe; Carbon Source: CH_4

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

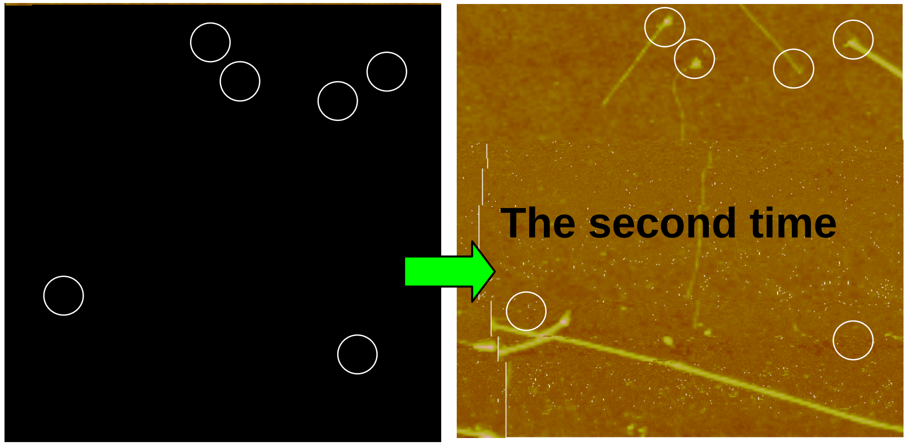
Growth Process:



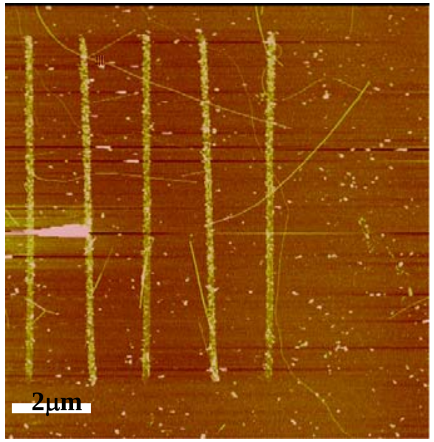
Questions:

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

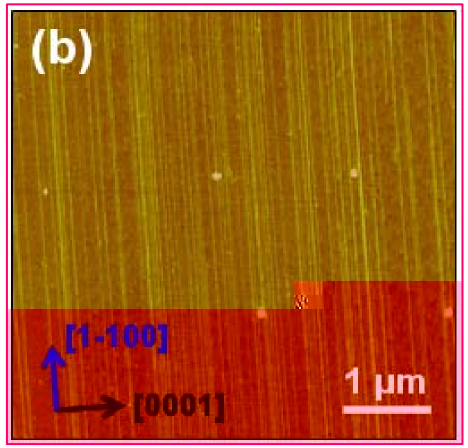
Controlled CVD Growth of SWNTs on Surface



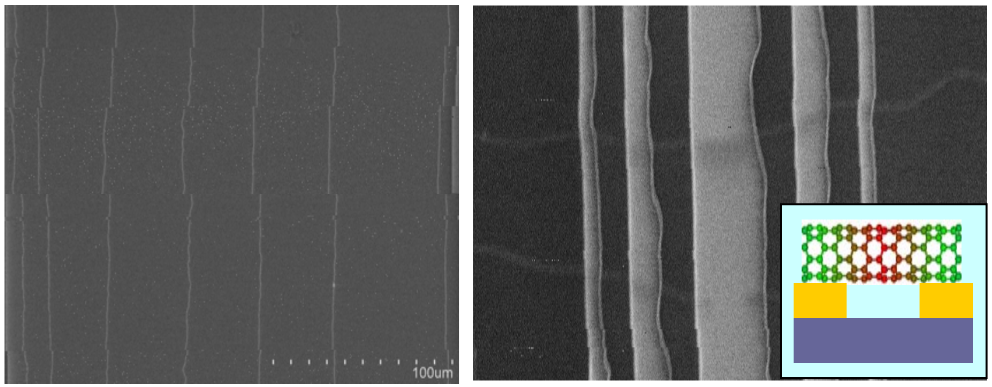
J. Phys. Chem. B. 2004, 108, 12665



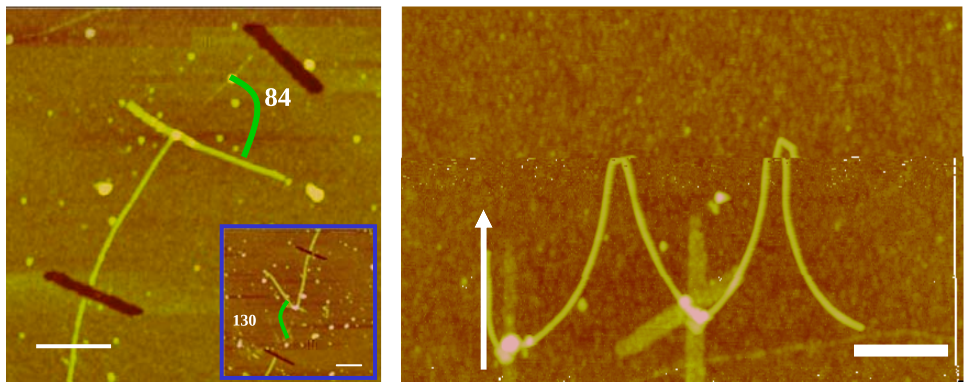
J. Phys. Chem. B, 2005, 109, 10946



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

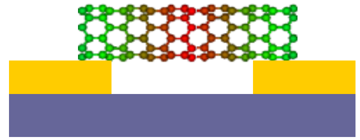
3 What architecture should the nanotube device have ?

4 How to integrate trillions of individual nanotube devices ?

Outline

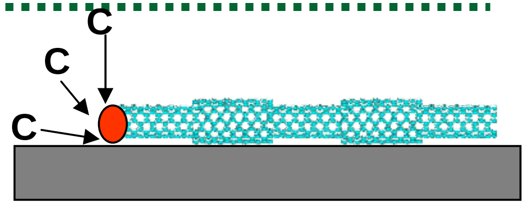
✓ **Control of local deformation of SWNTs**

—— Growth on designed surface



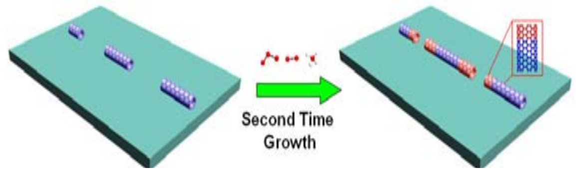
✓ **Control of local tube diameters of SWNTs**

—— Temperature-oscillation growth



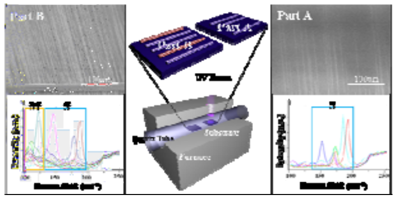
✓ **Control of chirality of SWNTs**

—— Cloning growth



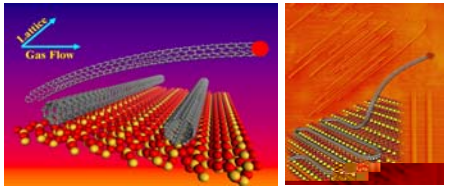
✓ **Control of metallic-/semiconducting- of SWNTs**

—— UV irradiation assistance CVD growth



✓ **Control of local conformation and architectures**

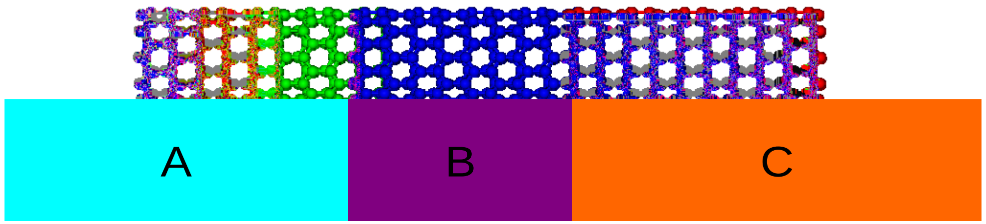
—— Cooperative growth of floating and lattice oriented modes



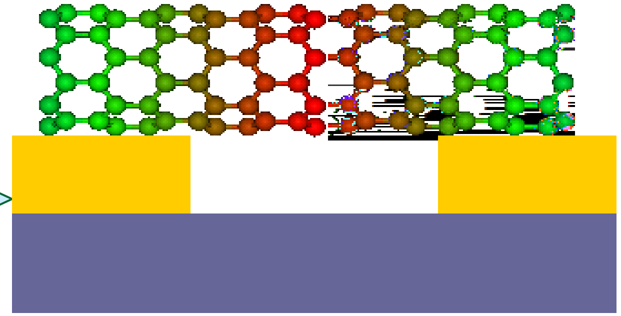
Control of local deformation of SWNTs

—— Growth ormdesigned surface

Substrate-Induced Band Structure Variation

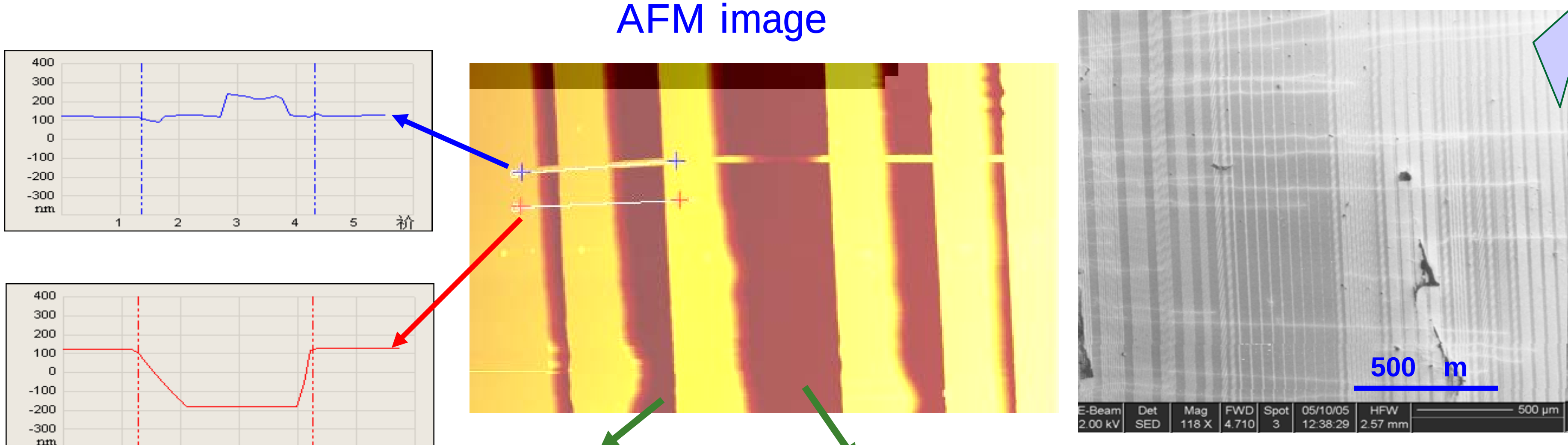


The goal



First experimental system

AFM image

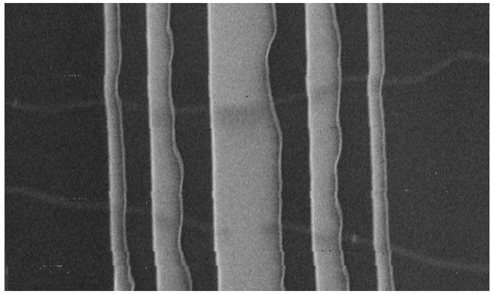


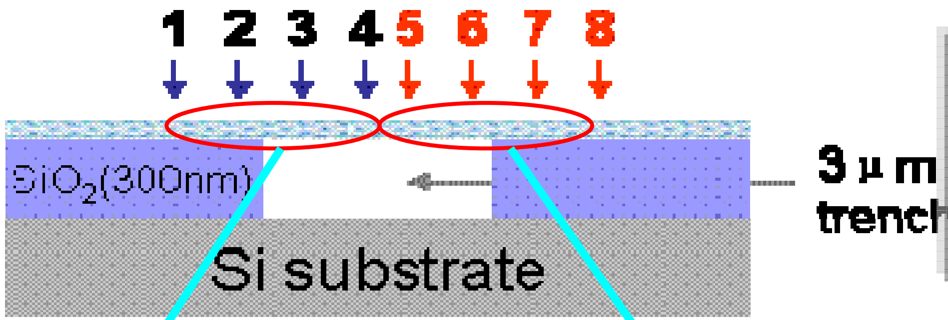
3 m

6 m

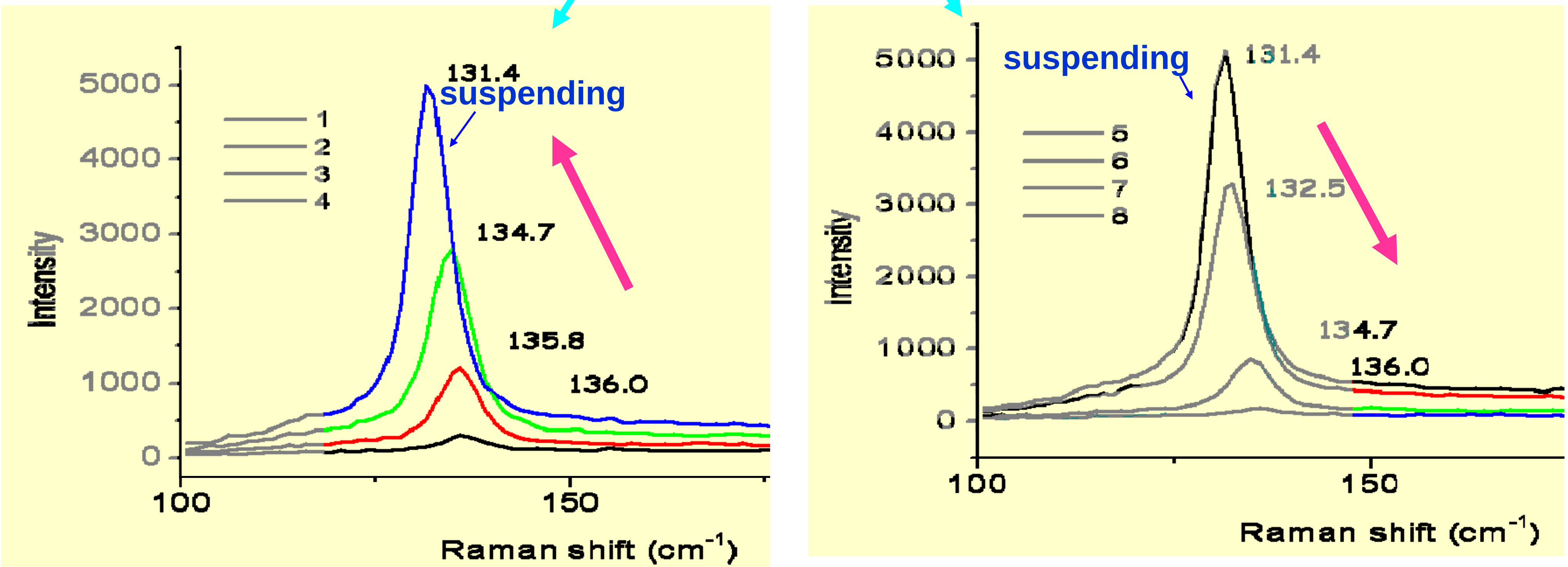
SEM image

Raman Mapping of Partially Suspended SWNT



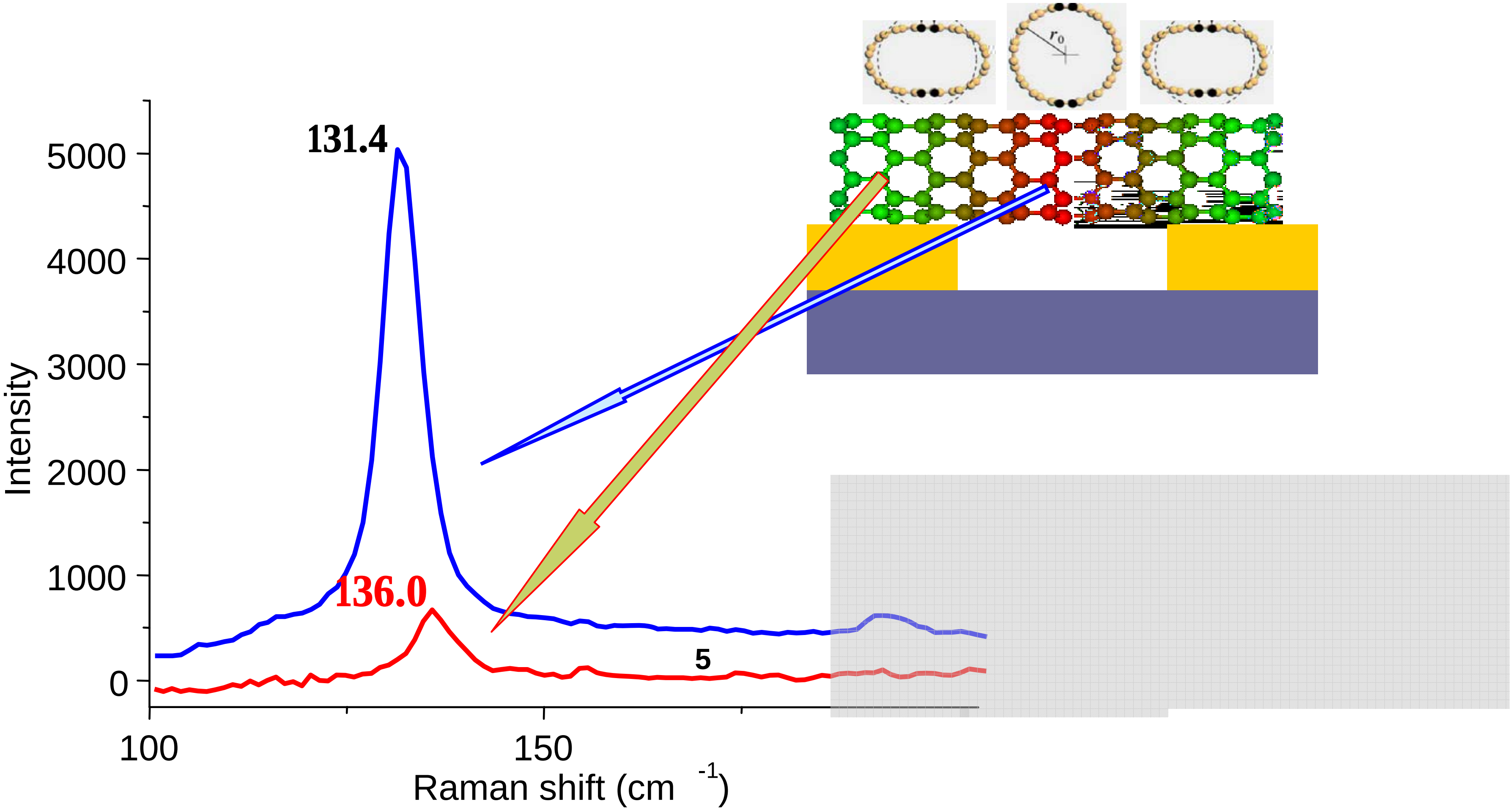


- λ_{laser}=632.8nm
- E_{laser}=1.96ev
- Cumulating time:10s

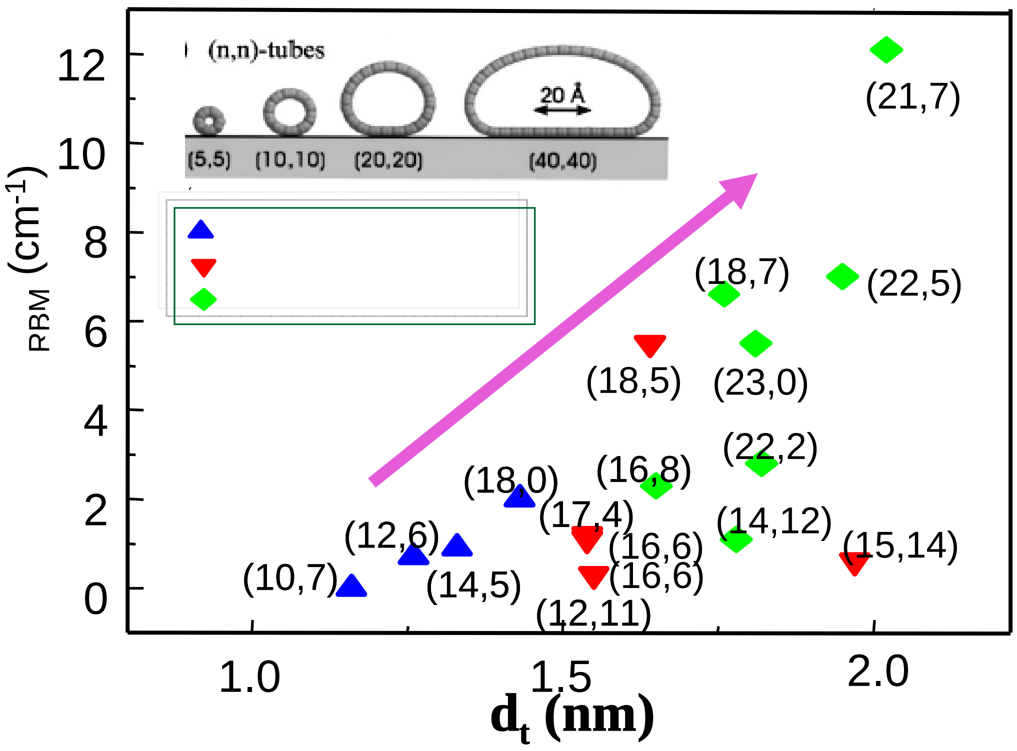


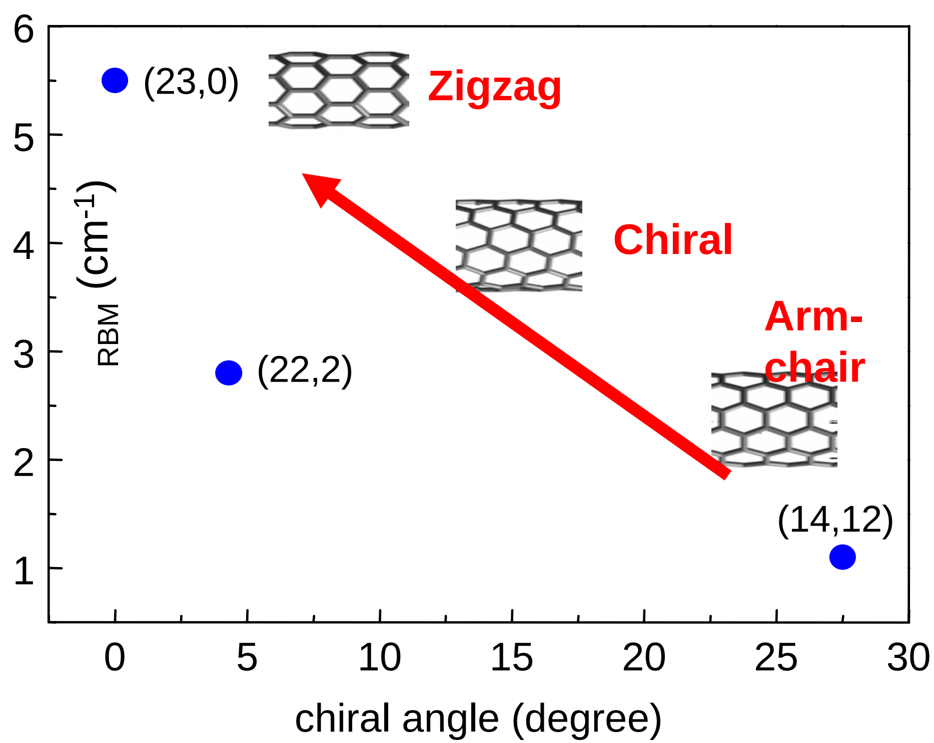
J Zhang et al, J. Am. Chem. Soc, 2005,127,17156

What is the Origin of Raman Spectrum Variation ?



Dependence of RBM on Diameter and Chiral Angle





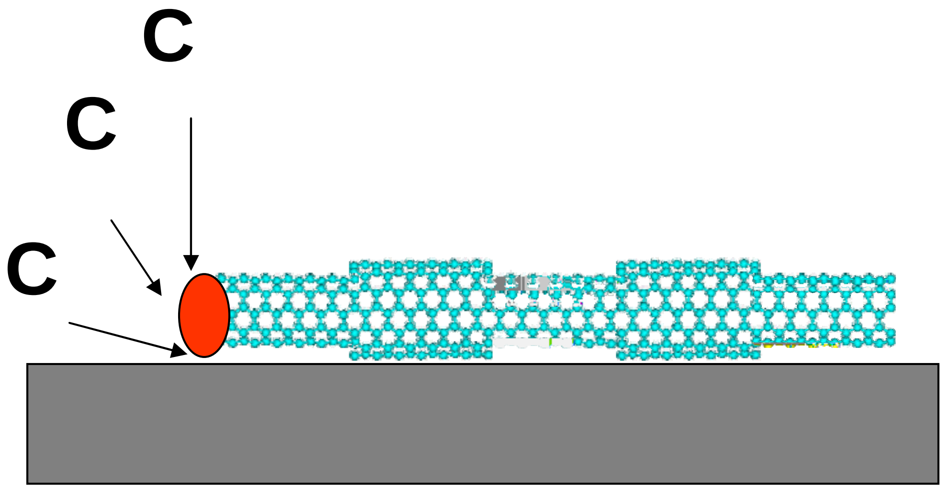
Δ RBM d_t

Δ RBM

Good agreement with theoretical work about radial deformation.

Band Structure Variation between Suspended and Non-suspended SWNT

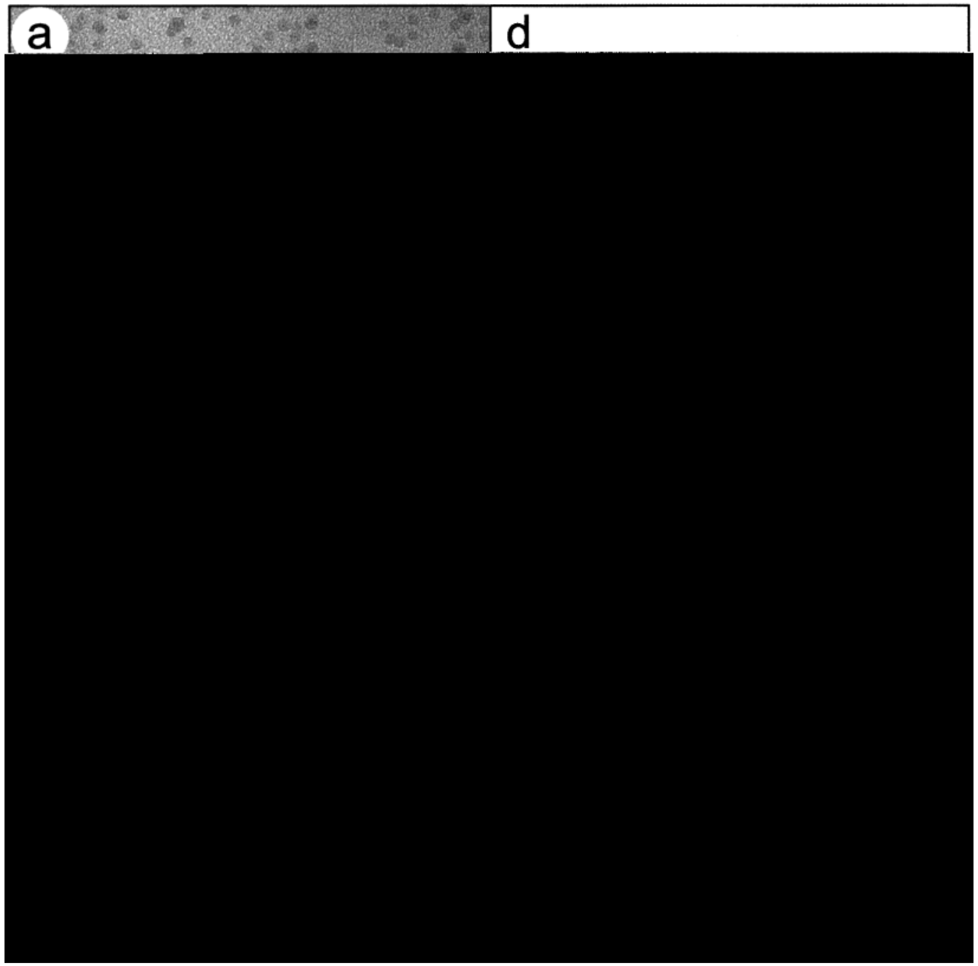
No.	Location	ω_{RBM}(cm^{-1})	I_{AS}/I_S	E_{ii}	E_{ii}(eV)	ΔE_{ii}(meV) (SiO_2-Sus)	(n,m)	(2n+m) MOD3
1	Suspended	282.7	0.12	E22S	1.9522	-3.1	(7,5)	1
	SiO_2	282.7	0.085		1.9491			
2	Suspended	243.6	1.26		1.9736	-4.8	Difficult	
	SiO_2	244.8	0.95		1.9688			
3	Suspended	200.4	0.13	E11M	1.9514	0	(13,4)/(14,2)/(15,0)	0
	SiO_2	200.4	0.14		1.9511			
4	Suspended	187.3	0.13	E11M	1.9517	+0.9	(11,8)	0
	SiO_2	188.3	0.15		1.9526			
5	Suspended	169.7	0.40	E33S	1.9584	-2.1	*(14,7)*	2
	SiO_2	169.4	0.28		1.9563			
6	Suspended	159.7	0.94	E33S	1.9640	-0.6	(12,11)/(16,6)/(17,4)	2
	SiO_2	159.8	0.79		1.9634			
7	Suspended	156.4	0.91	E33S	1.9671	-9.4	(12,11)/(15,8)/(20,1)	2
	SiO_2	156.7	0.39		1.9577			
8	Suspended	148.3	1.16	E33S	1.9640	-3.7	*(16,8)*	*1*
	SiO_2	148.2	0.60		1.9603			
9	Suspended	129.5	2.11	E44S	1.9698	-14.1	(24,1)/(18,10)/(19,8)/23,3)	1
	SiO_2	129.9	0.44		1.9557			
10	Suspended	116.8	0.55	E44S	1.9588	+4.3	(25,3)/(23,7)/(20,10)	2
	SiO_2	116.8	1.20		1.9631			
11	Suspended	115.9	1.50	E44S	1.9648	+2.6	(23,7)/(20,10) (25,3)	2
	SiO_2	115.7	1.25		1.9672			
12	*Suspended*	*110.7*	*1.01*	E44S	*1.9670*	*+26*	*(28,0)*	*2*
	SiO_2	*110.8*	*3.07*		*1.9810*			

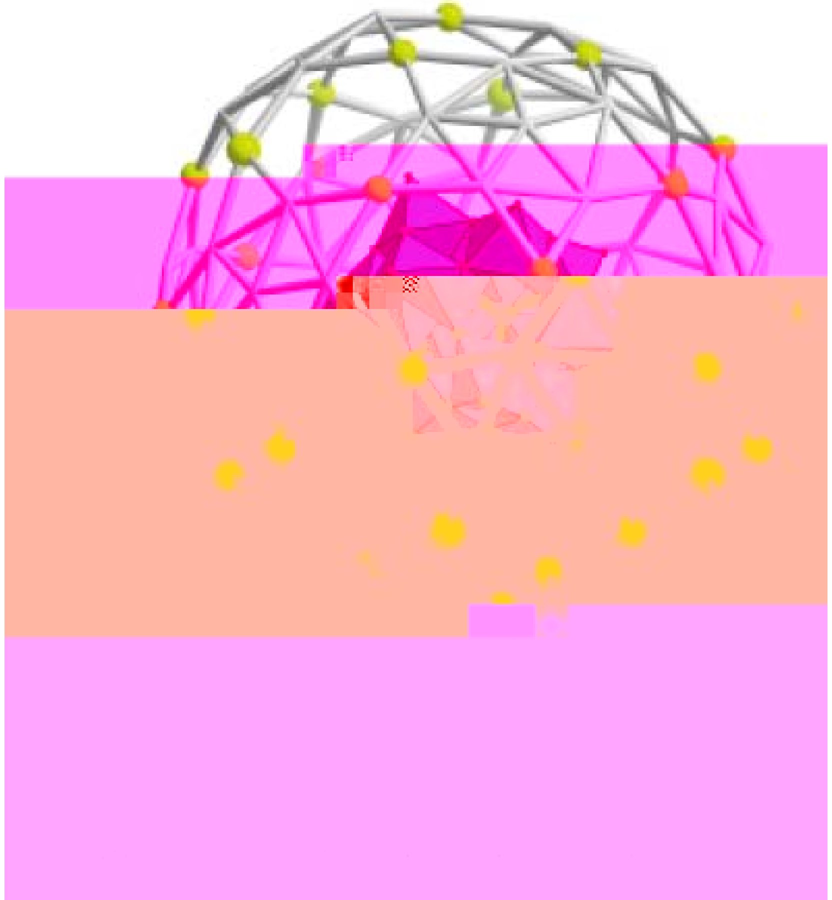


Control of local tube diameters of SWNTs

—— Temperature-oscillation growth

Controlling the Diameter of SWNT by Catalyst Particle

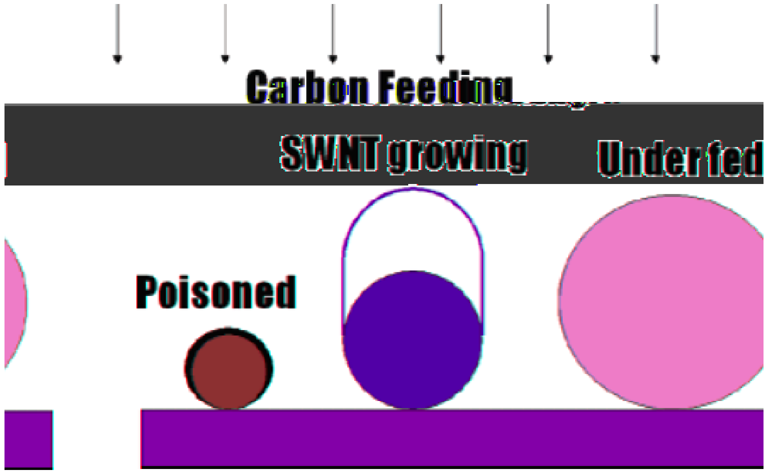


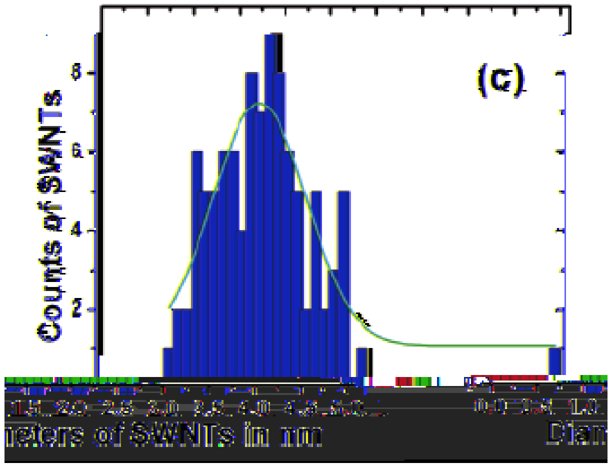


J. Phys. Chem. B. 2002,106, 2429-2433

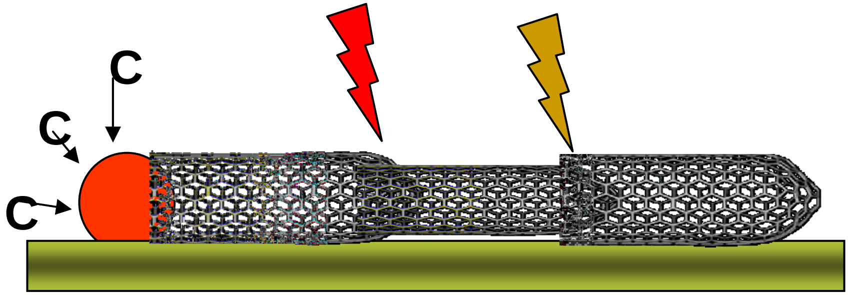
J. Am. Chem. Soc. 2002, 124, 13688

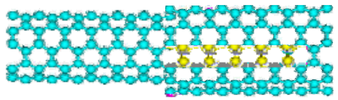
Controlling the Diameter by Carbon Feeding





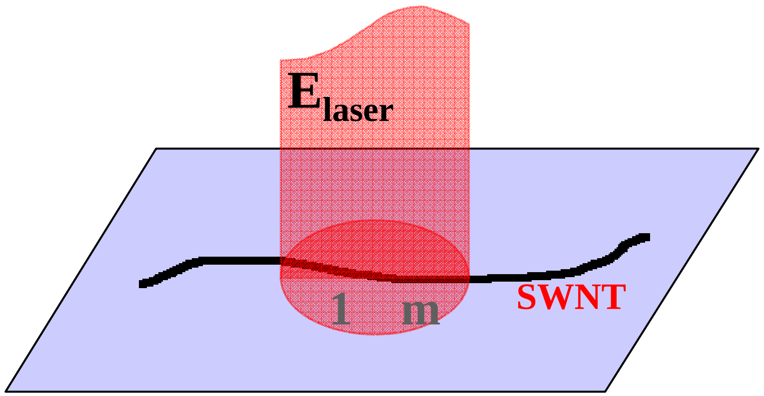
Our Approach: Tune the Diameter of SWNTs by Temperature



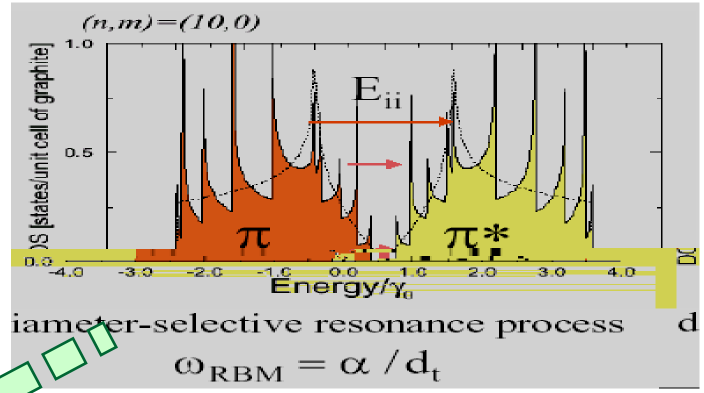


Liu, J. et. al. J. Phys. Chem. B. 2006,110,20254-20257

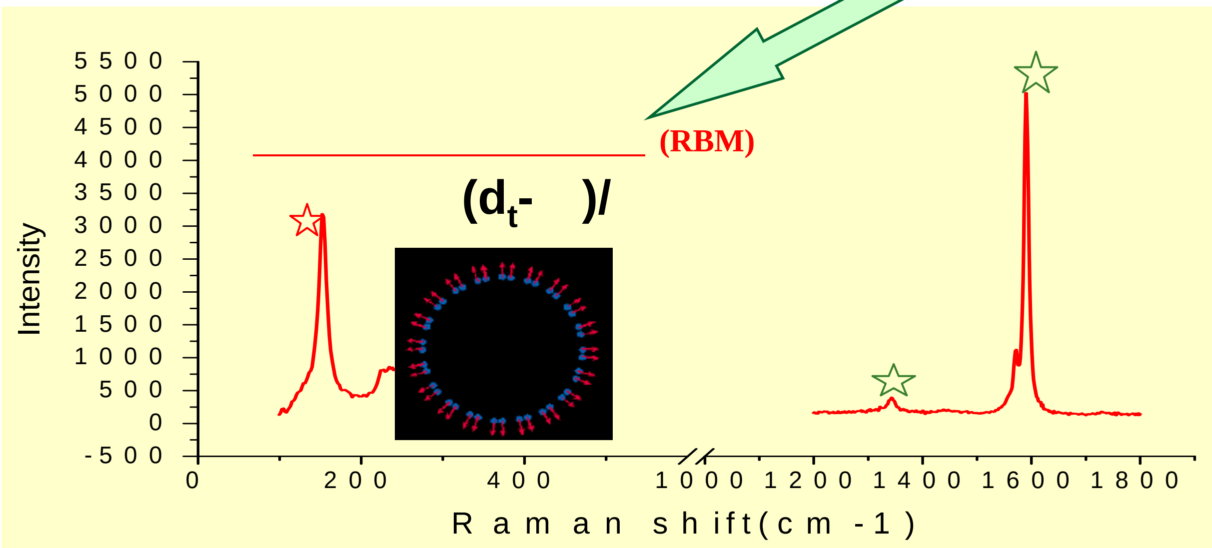
Micro-Resonance Raman Spectrum of Individual SWNTs

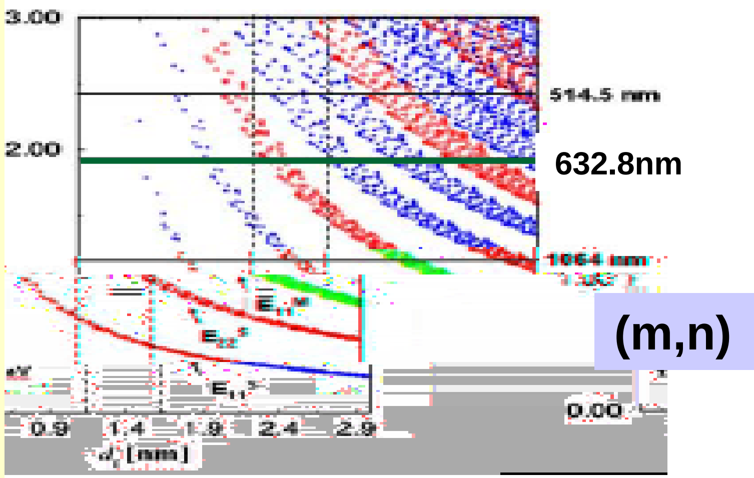


Micro-Raman spectroscopy



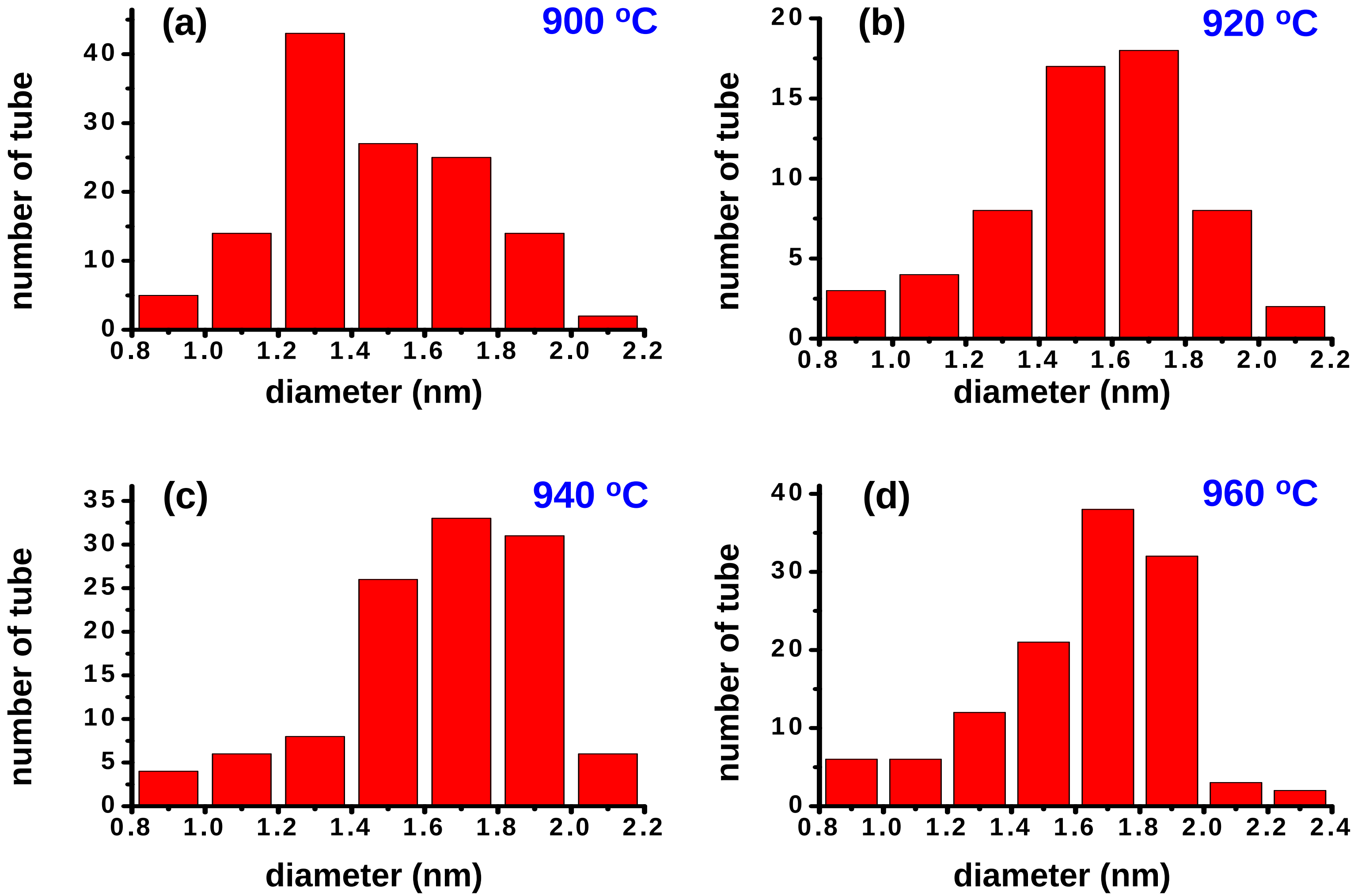
Resonance condition: $E_{laser}=E_{ii}$





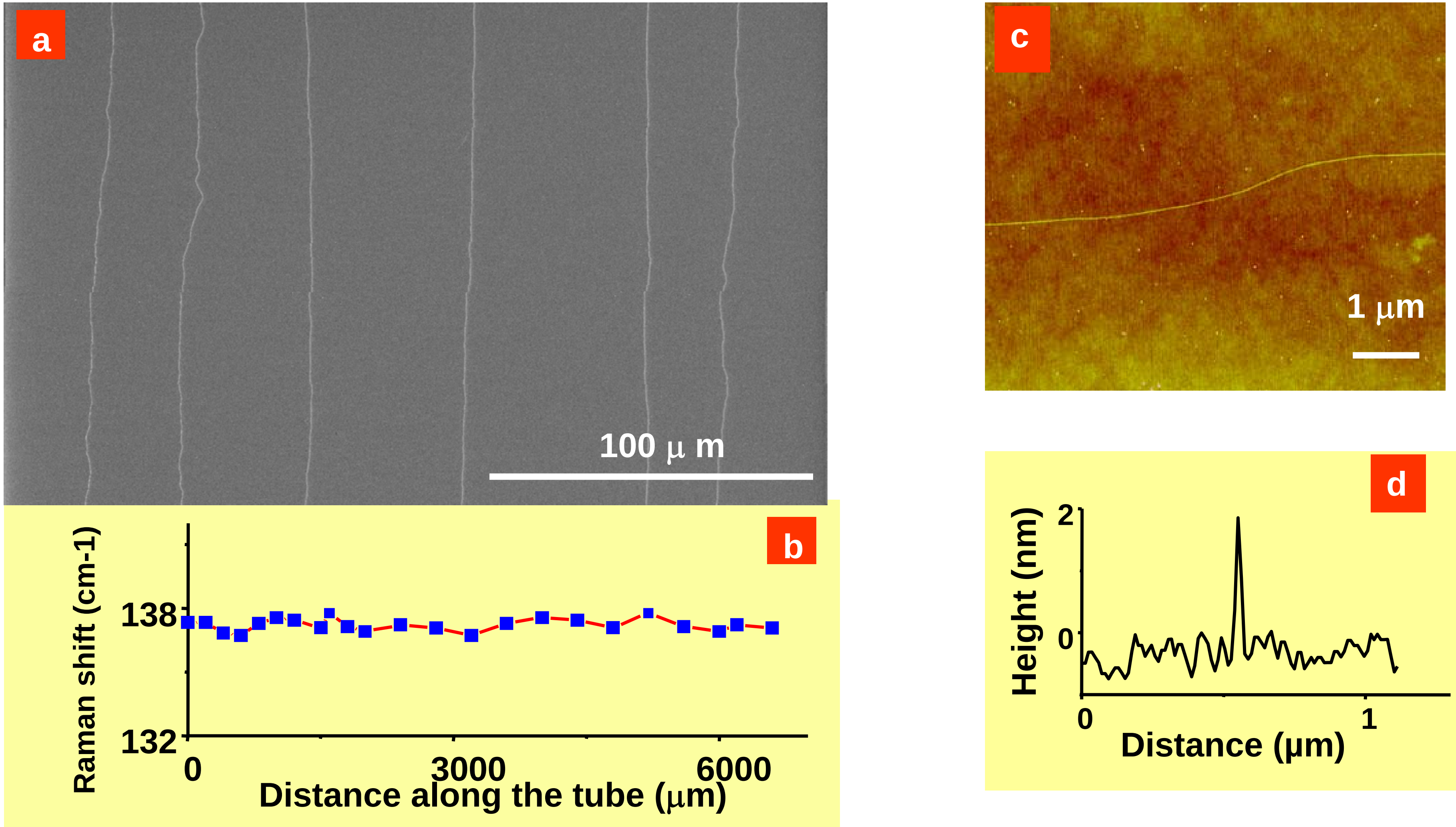
A power tool for both the atomic and electronic structure of SWNT !

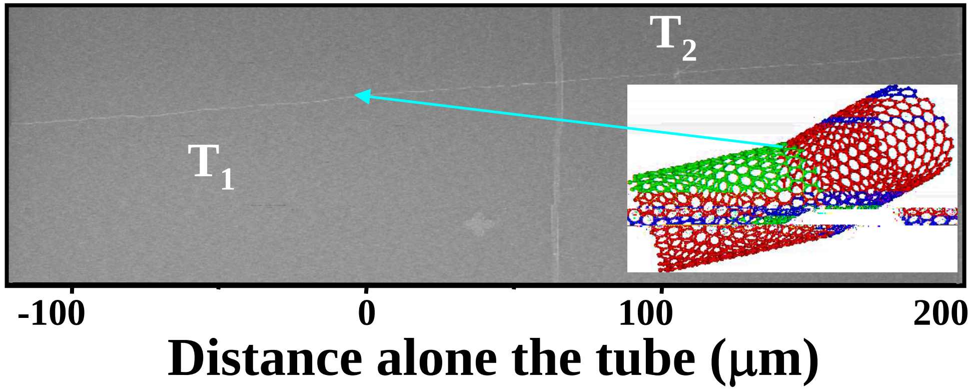
Growing SWNTs at Different Temperature

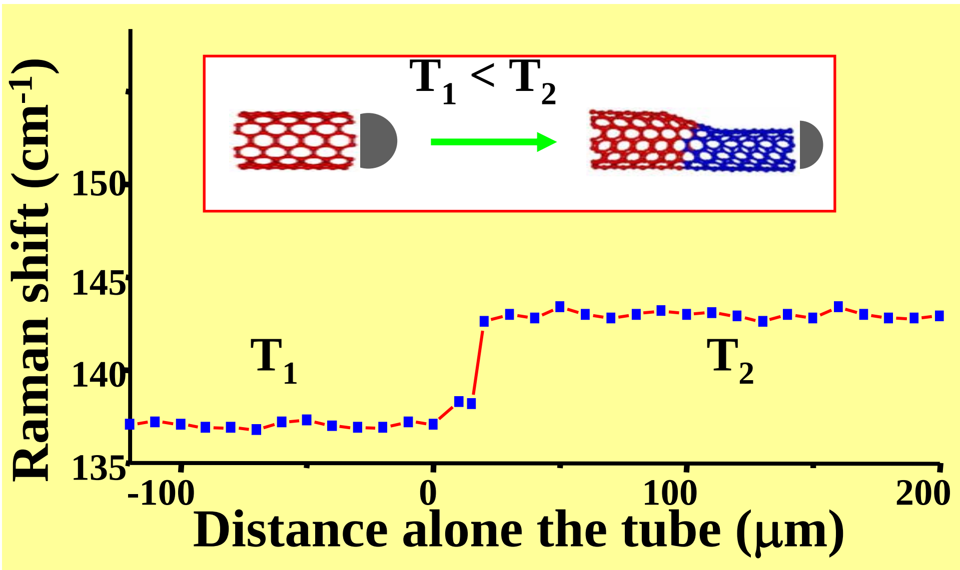


The catalyst nanoparticles might sinter or collide with each other at the high temperature

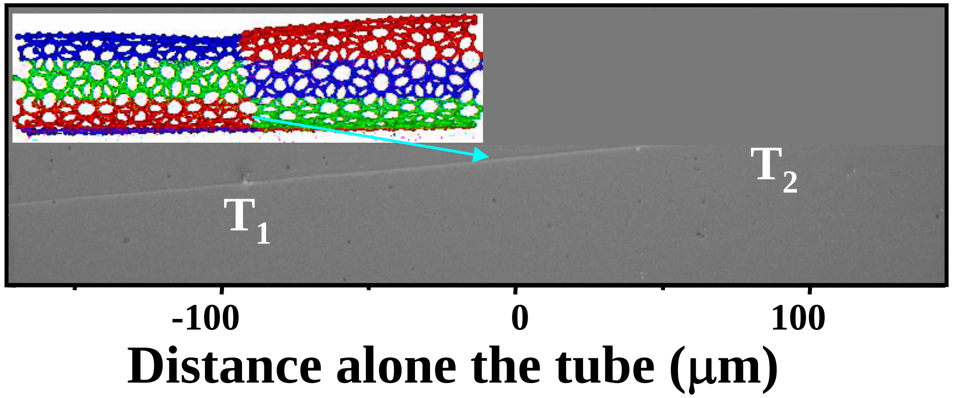
Constant-temperature CVD

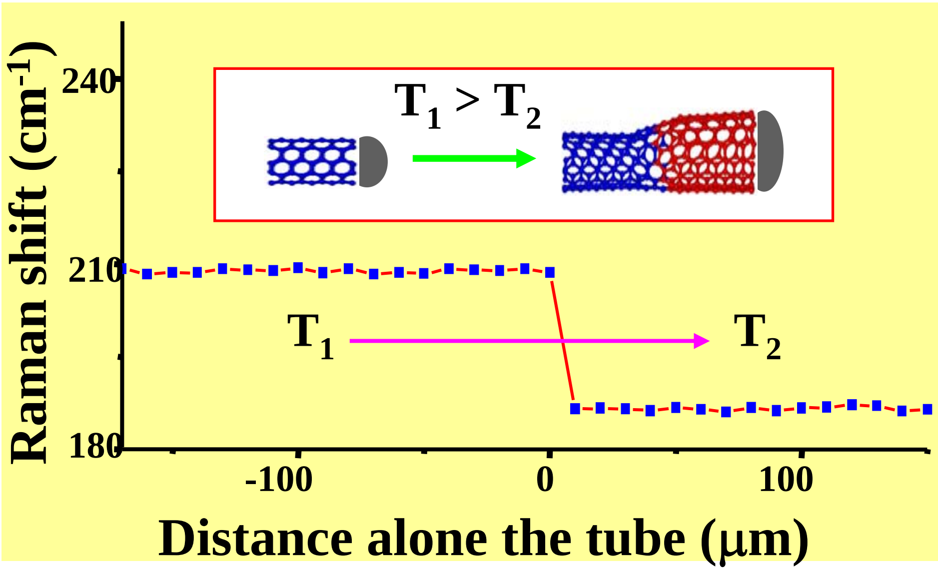


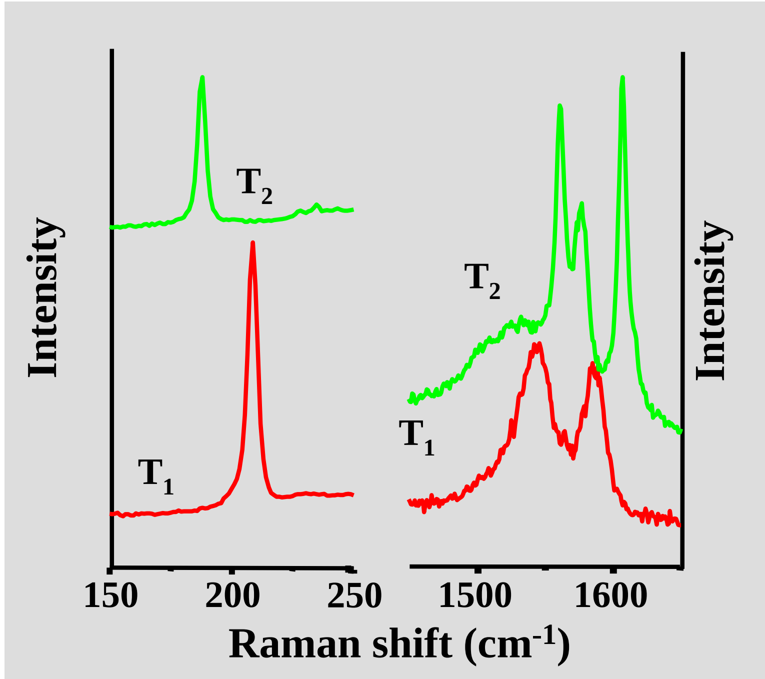

T2
T1
-100
0
100
200
Distance alone the tube (μm)

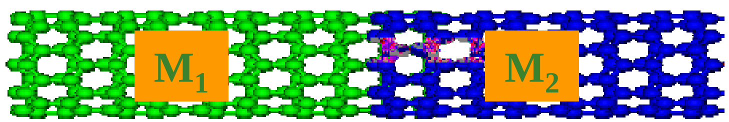

T1 < T2
Raman shift (cm-1)
150
145
140
135
T1
T2
-100
0
100
200
Distance alone the tube (μm)

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





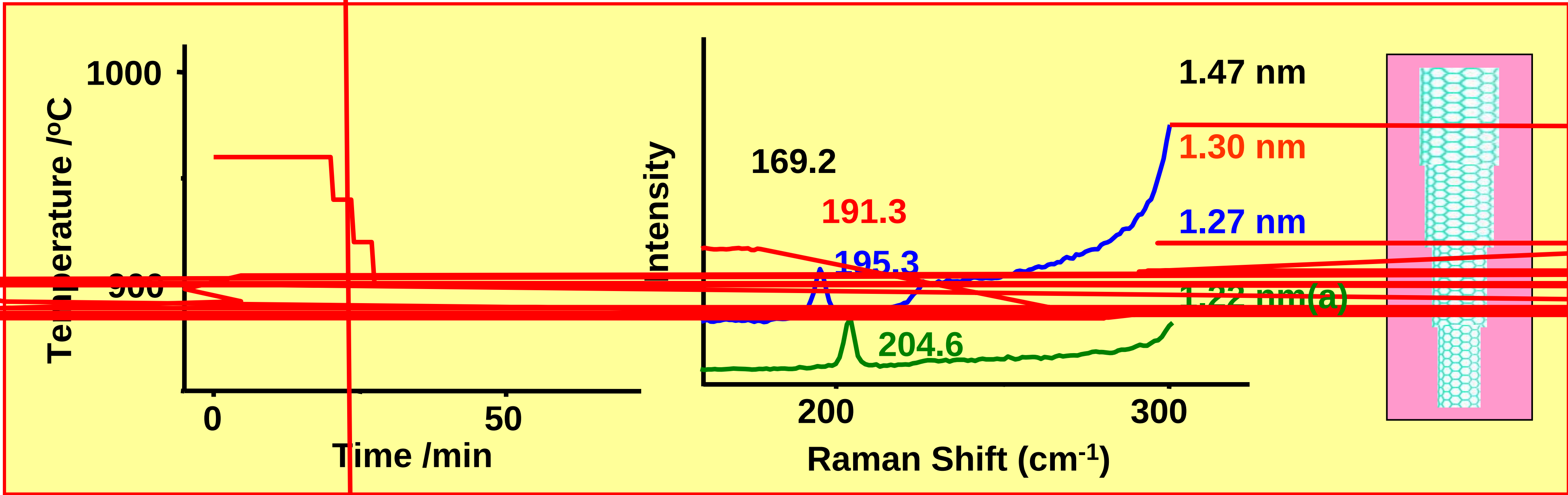


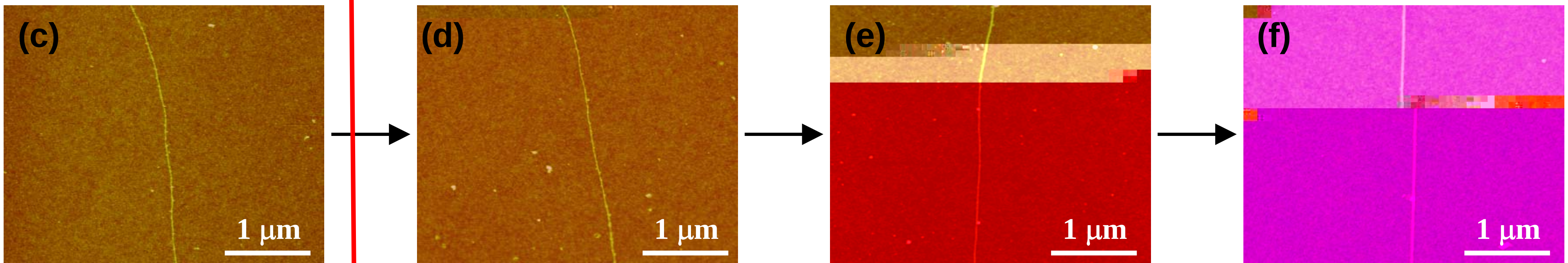


Metallic Metallic Nanojunction

Controlled Thinning of SWNTs via Temper2NTs vmper2re Step

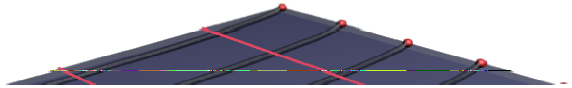
Controlled Thickening of SWNTs via Temperature Step-Down



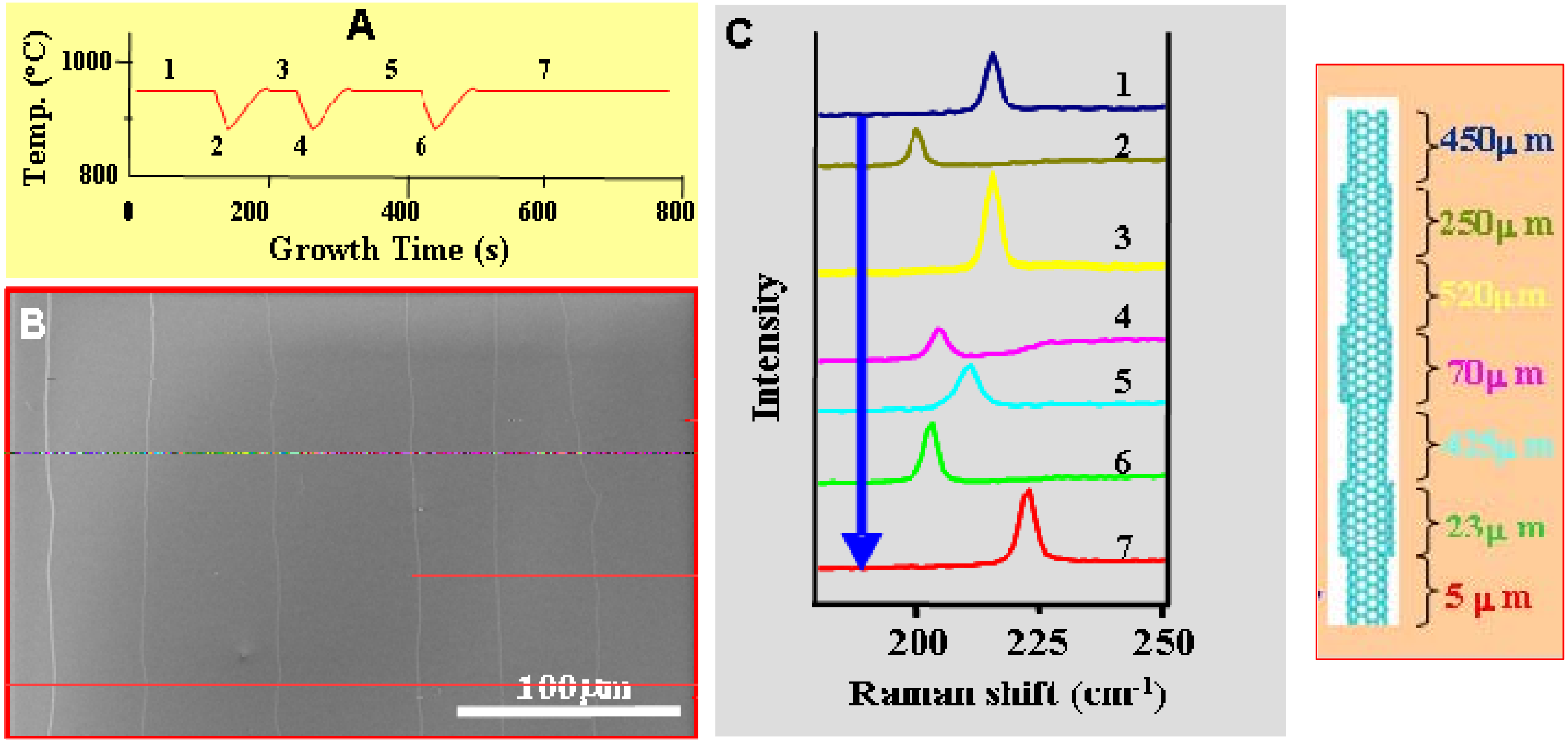


1.34 0.04 nm 1.45 0.03 nm 1.69 0.04 nm 1.98 0.05 nm

900 °C → 920 °C → 940 °C → 960 °C



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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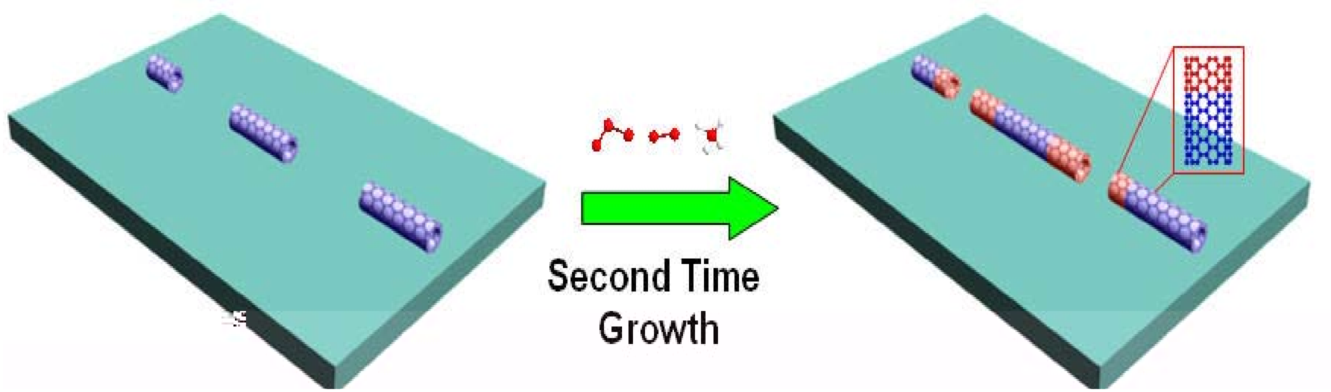
But carbon nanotubes could, in the future, provide more than just thermal management, they could form the basis of electronic devices themselves. To realize such a goal, it will be necessary to find a means of creating intramolecular junctions in a controlled manner. Researchers from Peking University, 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].

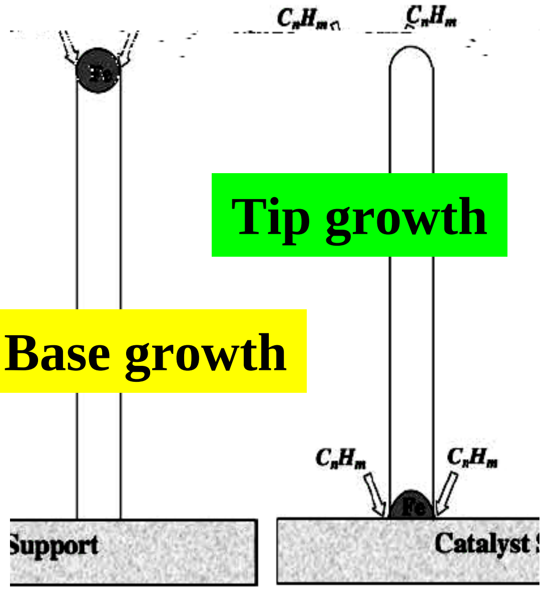
It is currently accepted that the size of the catalytic particle used to grow a nanotube determines its diameter. However, the Chinese researchers observe that the diameter of a SWNT varies with growth temperature during catalytic CVD, even with the same catalytic particle. The results show that if the 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.



Control of chirality of SWNTs

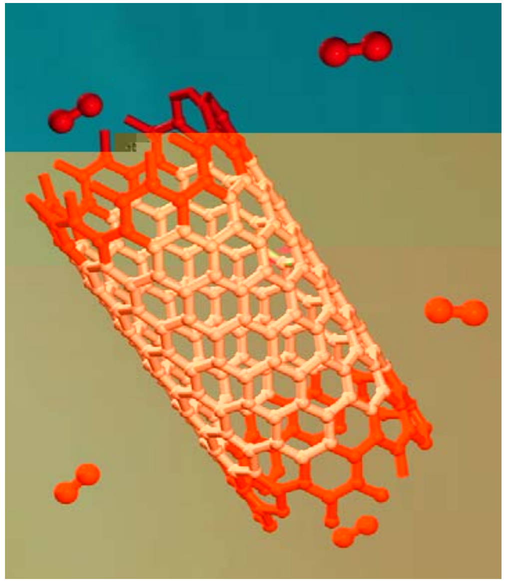
—— Cloning growth



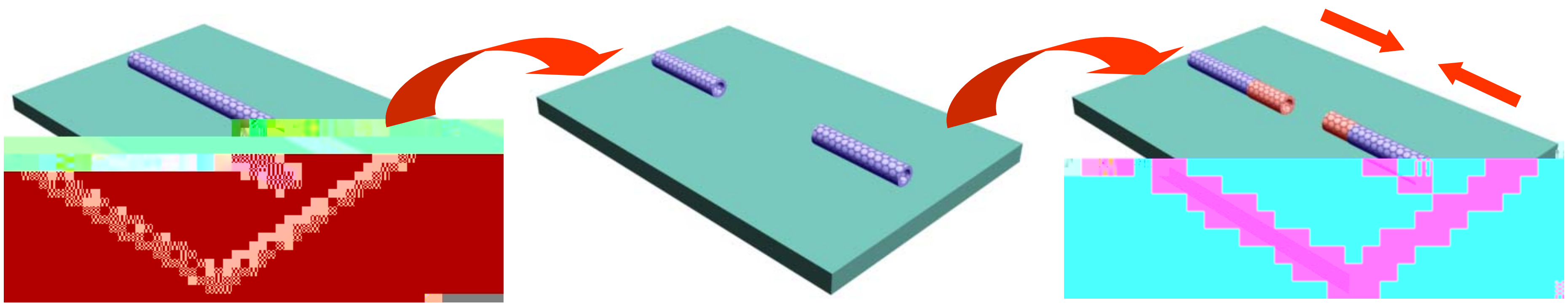
Growth catalyst:

Fe, Co, Ni, Cu, Ag, Au, Pt, Pd, C_{60}, Si/SiC, Ge/SiC, SiO_2, TiO_2, Al_2O_3, Rare earth oxides

Why not the chemically-active open-cap nanotube ?



Open-end growth mode

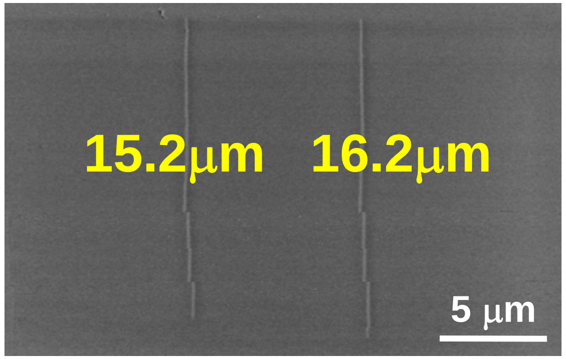


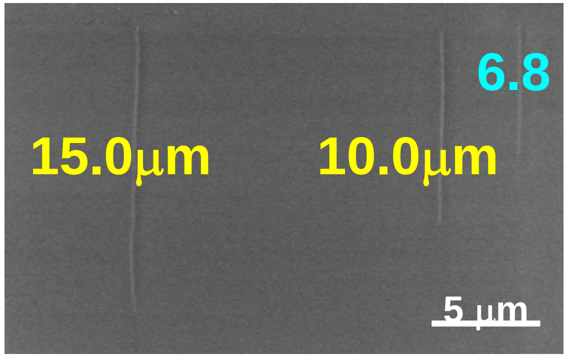
Original "seed" catalyst | **EBL+O_2 plasma** | **Second growth**

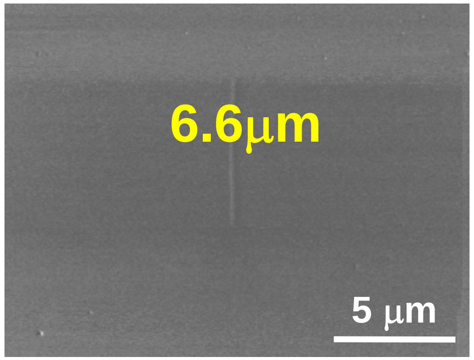
Chinese patent: 2008 1 0222216.7

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

Cloning SWNTs on Quartz Surface

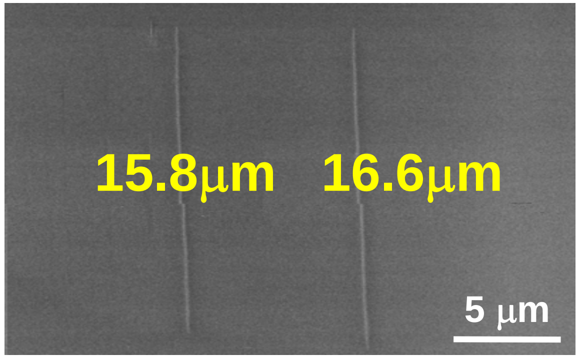


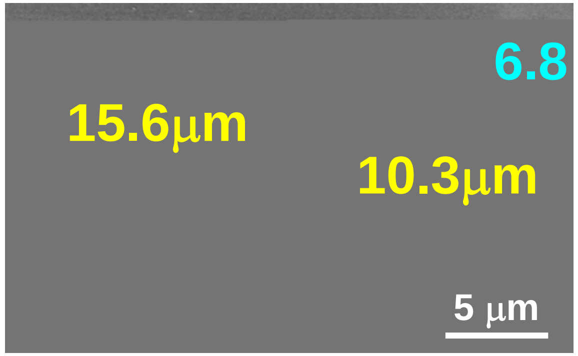


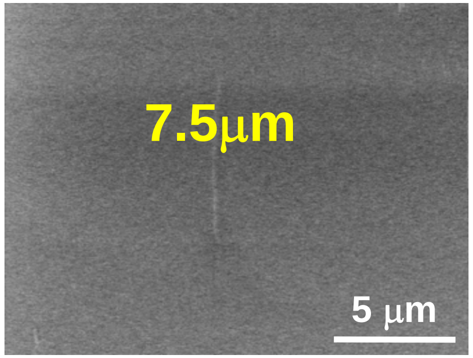


Tube length increase:

0 μm – 1μm

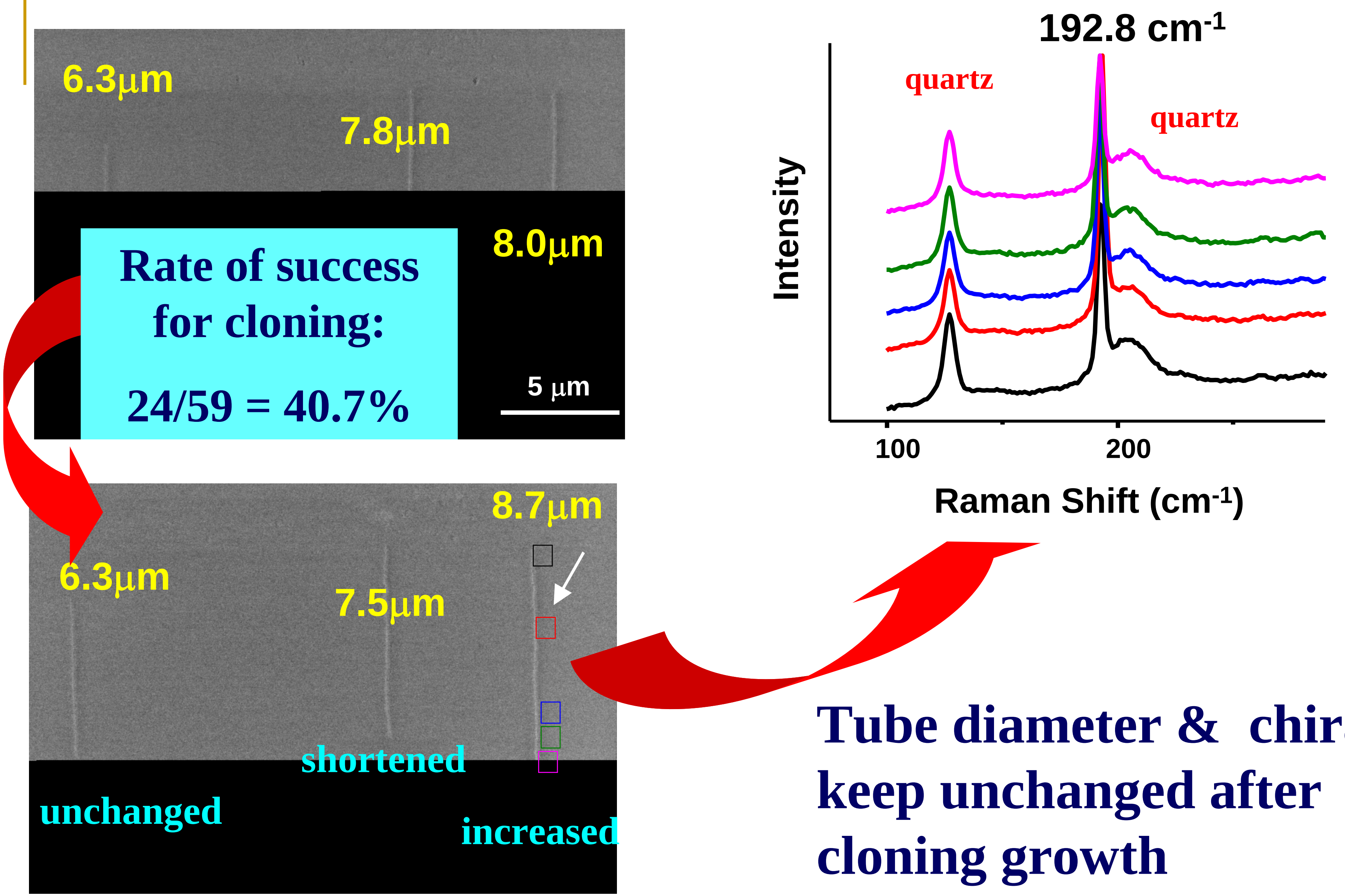






Before growth

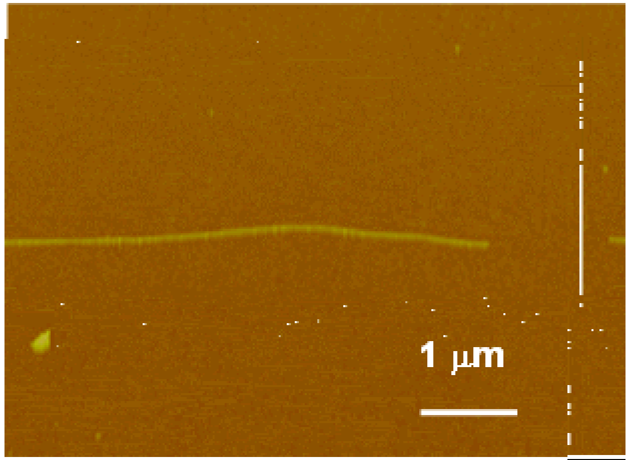
After growth

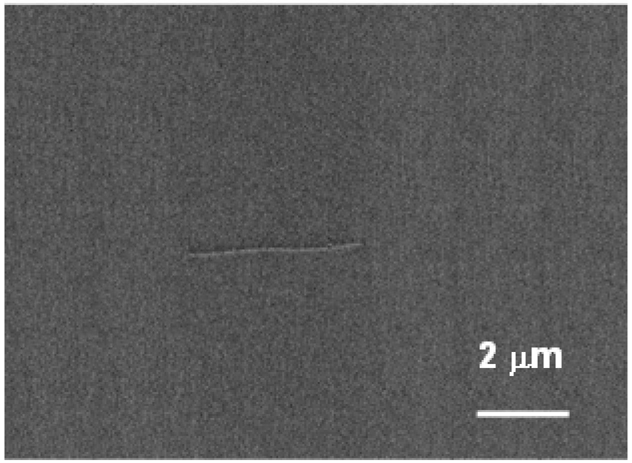


Tube diameter & chirality keep unchanged after cloning growth

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

Cloning SWNTs on SiO_2/Si Surface





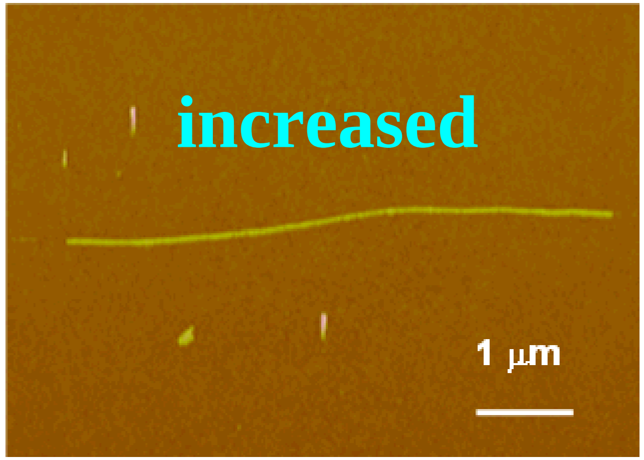
Tube length increase:

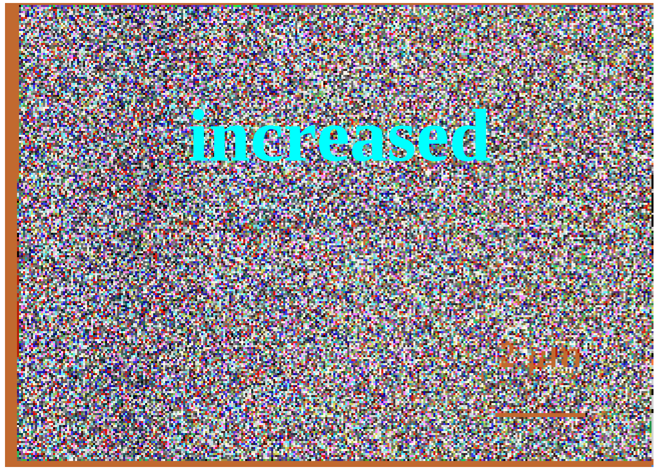
0 μm – 4.6 μm

Rate of success for cloning:

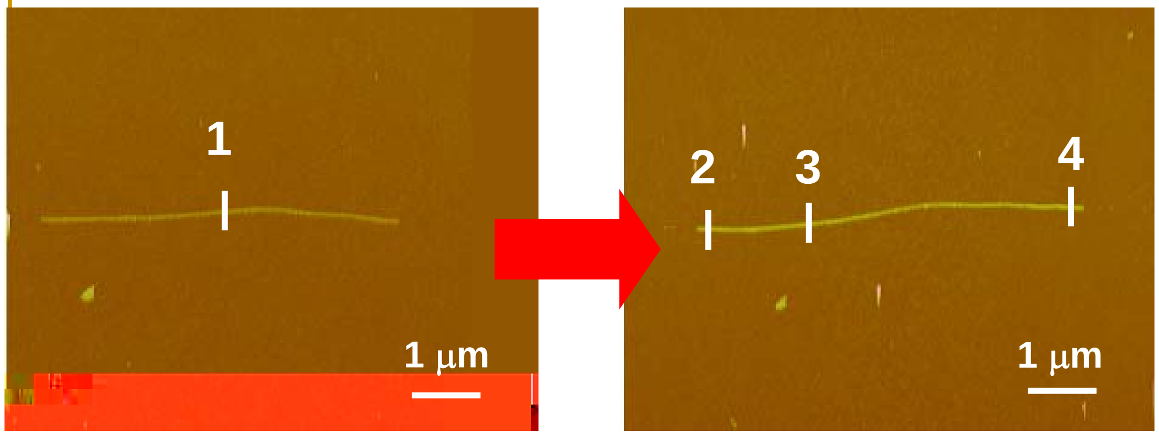
56/600 = 9.3%

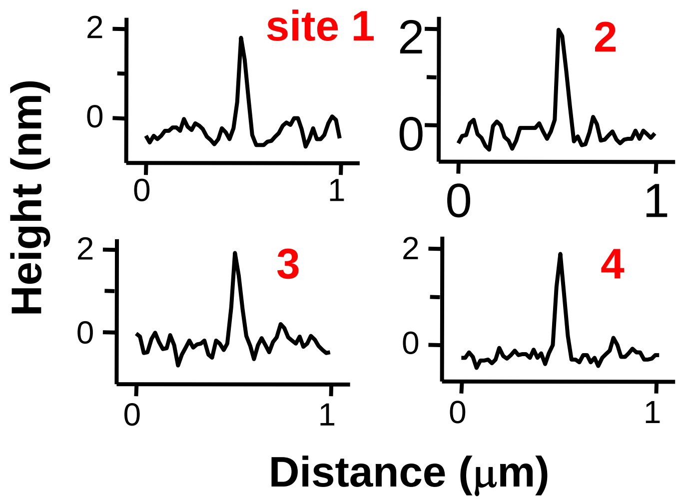
- *$CH_4/C_2H_4/H_2$=100/5/300*
- *Growth T=975°C for 15min*





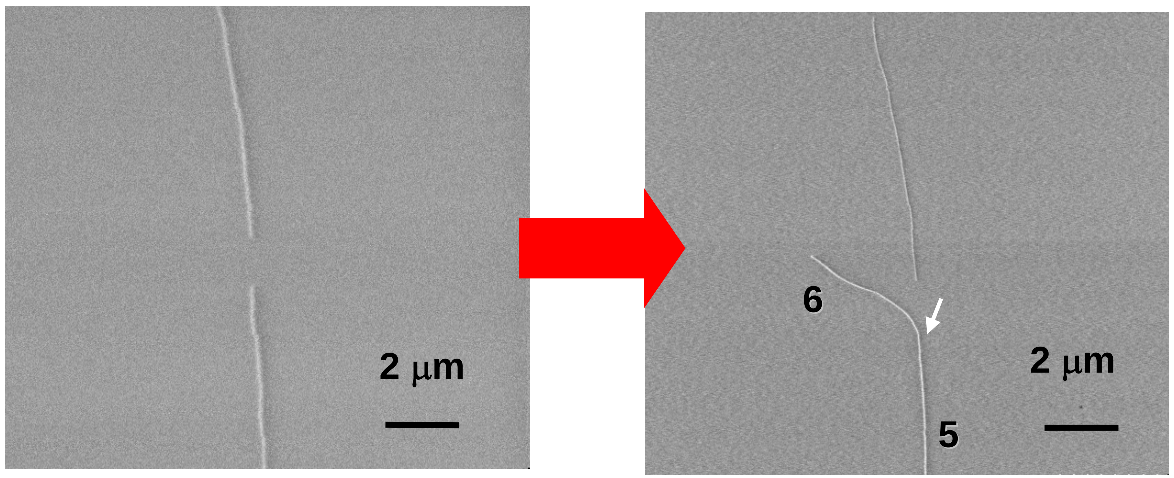
Before growth | **After growth**

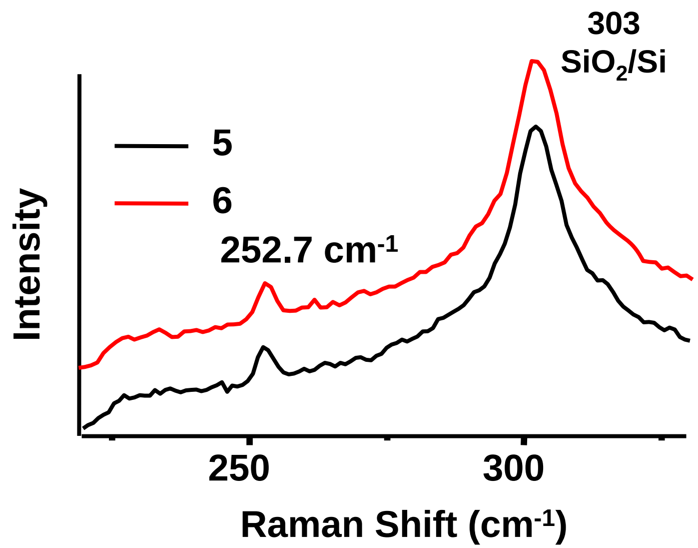




Before growth

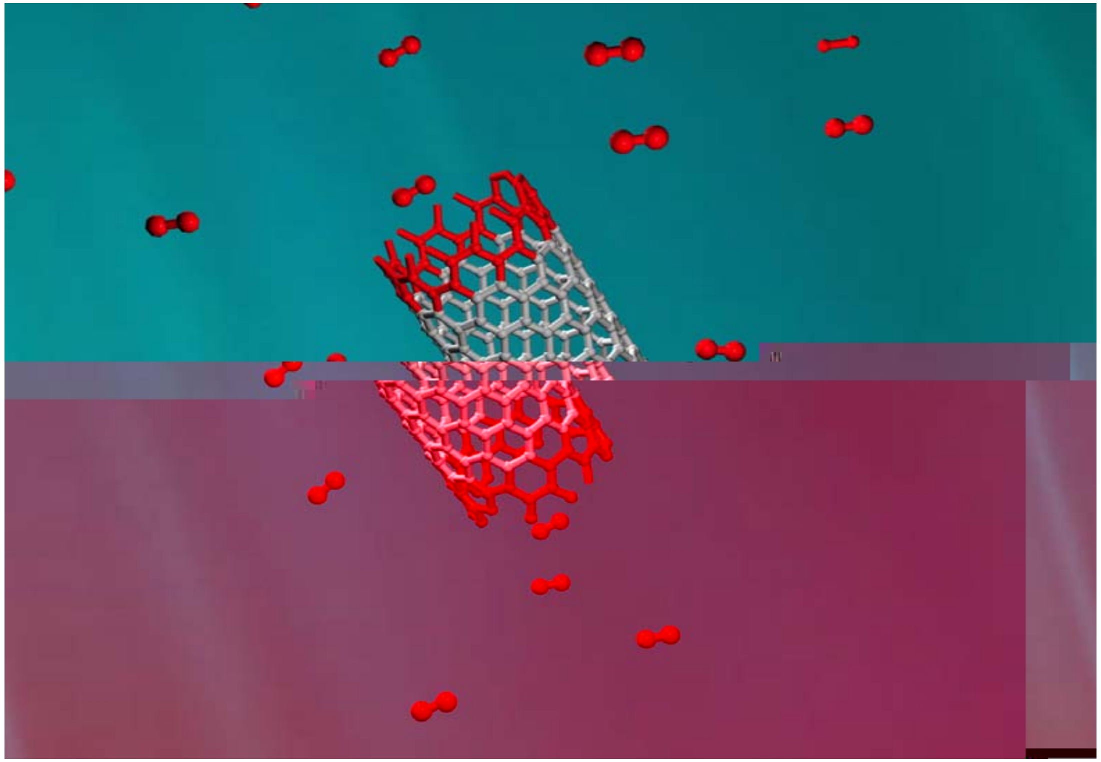
After growth

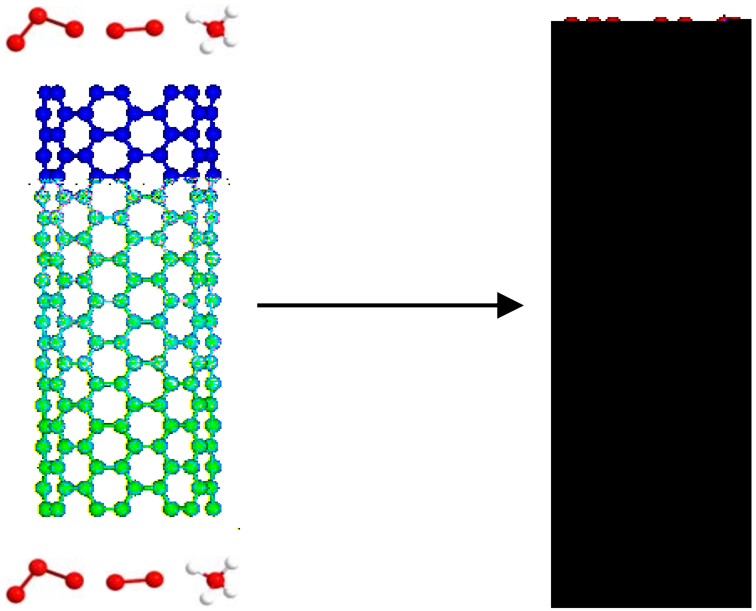




AFM and Raman evidence for the diameter & chirality maintenance

Open-End Growth Mechanism





“VS” growth model ?

featured highlight

Carbon nanotubes: Perfect clones

Published online 29 June 2009

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

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).

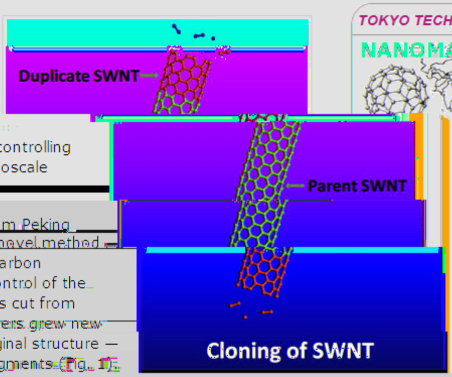


Fig. 1: Using open-end single-walled nanotubes (SWNTs) as seeds for a cloning growth process may solve current structural control issues.

Working with ultralong single-walled carbon nanotubes grown by chemical vapor deposition, Zhang's group first ...

lithography and oxygen plasma ion etching, the researchers prepared short, open-ended segments of the nanotubes as seeds. These small sections were then heat ... to 700 °C to remove any impurities.

... over the seed segments. Using atomic force and scanning electron microscopy, the research team observed new growth of several micrometers in length extending from the seeds. Raman spectroscopy confirmed that the newly grown nanotube segments retained the original seed structure.

According to Zhang, ... a mixture of acetylene and methane gases. "We used acetylene to facilitate the ... decomposition of methane gas into carbon radicals. If we didn't use acetylene, or, if the growth temperature was below 945 °C, no amplified growth occurred," he says.

Instead of requiring an external additive, the growth mechanism discovered by Zhang uses the open ends of the nanotubes themselves as catalysts. The seed segments predetermine the nanotube structure, and any new growth via carbon radicals retains this arrangement.

The researchers reported that, on a quartz substrate, over 40% of the initial seeds produced new cloned segments. "We think if the open-ended segments were suspended, ...

Zhang and colleagues are now undertaking large-scale growth trials of the single-walled carbon nanotube clones.

Reference

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

Author affiliation

1. Beijing National Laboratory for Molecular Sciences (BNLMS), Key Laboratory for the Physics and Chemistry of Nanodevices, State Key Laboratory for Structural Chemistry of Unstable and Stable Species, College of Chemistry and Molecular Engineering, Peking University, Beijing 100871, China
*E-mail: jinzhang@pku.edu.cn

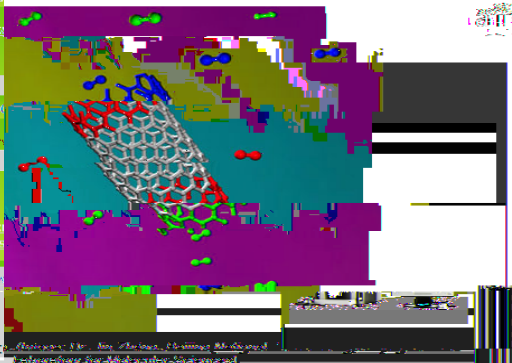
Posted: April 3, 2009

'Cloning' might solve the chirality control issue of nanotube production

(*Nanowerk Spotlight*) Notwithstanding the tremendous amount of research that has gone into the field of carbon nanotubes, the synthesis of single-walled carbon nanotubes (SWCNTs) with controlled chirality ... still has not been achieved. Current production methods for carbon nanotubes result in ... different diameter, length, chirality and electronic properties, all packed together in bundles, and often blended with some amount of amorphous carbon. The separation of nanotubes according to properties remains a technical challenge. Especially SWCNT sorting is a challenge because the composition and chemical properties of SWCNTs of different types are very similar, making conventional separation techniques inefficient.

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

"We found that an open-end single-walled carbon nanotube, which served as seed, could be continually grown via an open-end growth mechanism," Jin Zhang tells Nanowerk. "The new 'cloned' SWCNTs and ...



... professor of chemistry and molecular engineering at the Beijing National Laboratory for Molecular Sciences, and his colleagues Zhongfan Liu, Yagang Yao, Chaoqun Feng, will understand the formation mechanism of single walled carbon nanotubes, but also growth of SWCNT with identical chirality into reality.

... mechanism might be an effective way for cloning of graphene from small graphene ... large scale cloning of single chirality SWCNT could lead to practical applications.

... their findings in the March 13, 2009 online edition of *Nano Letters* ("'Cloning' of Single-Walled Carbon Nanotubes via Open-End Growth Mechanism").

Zhang's team first grew ultralong (several tens of micrometers) SWCNTs on SiO_2/Si ... length is only limited by the substrate size, the hot zone of the furnace, and ... the ultralong SWCNTs were cut into short segments by electron beam ... oxygen plasma ion etching, and lift-off, which could be served as seeds/catalysts ... second growth.

SWCNT 'clones' were grown from the open-end parent SWCNTs by putting the open-... chemical vapor deposition (CVD) furnace to first get rid of -COOH and -OH at the end- ... which could help expose the active open-end, and then, by introducing CH_4 ...

... usually grew as much as a few micrometers in length and the longest length of ... µm" says Zhang. "We thought that if the second growth is not constrained by ... the open-end SWCNTs are suspending, the new SWCNTs will grow longer."

... in principle, the growth efficiency of cloning and the exact open-end growth ... which still need to be solved.

... than 600 short seed segments and found the yield of cloning is relatively low. "This yield can be greatly improved up to 40% by growing SWCNTs on quartz ...

... cloning is to verify the duplicate SWCNTs have the same chirality of the ... atomic force microscopy and micro resonance Raman spectroscopy ... determined that the parent nanotube and the duplicate nanotube had the ...

... open-end SWCNT catalyst (seed) is more suitable than other reported ... of SWCNTs.

... aggregate at high growth temperate. The metal catalyst nanoparticles usually ... temperature which will widen the diameter of SWCNTs grown by them. Secondly, ... directly add to the open-end and thus the chirality of new cloned SWCNTs will have ... the parent SWCNTs. Thirdly, our results support the idea that nanosize ... template for the formation of SWCNTs."

These findings by Zhang, a professor ... Laboratory for Molecular ... be not only helpful to ... turn the controllable g...

Moreover, this growth ... sheets. Furthermore, ...

The scientists reported ... Single-Walled Carbon ...

For their technique, Zhang ... substrate. The nanotube ... the growth time. Then, t... lithography (EBL), oxyg... and the stencil in the se...

In a third step, the SWC... end seeds in a chemica... functionalized SWCNTs ... and C_2H_2 carbon sourc...

"The cloned nanotubes u... amplified growth was 4.6 ... the substrate such as th...

While this strategy works ... mechanism are problems...

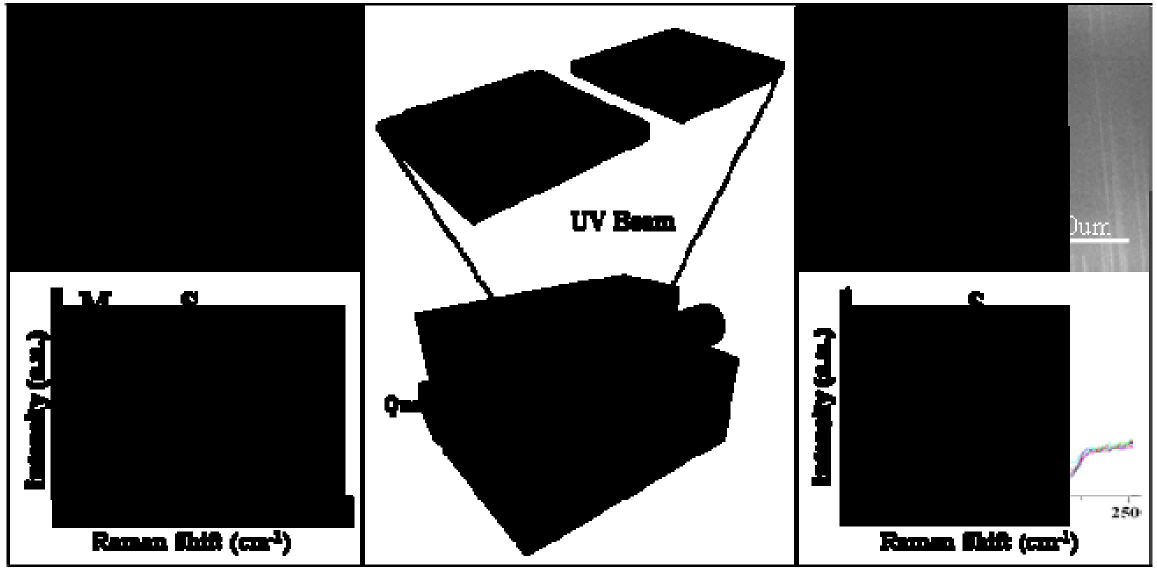
"We have measured mor... around 9%" says Zhang. ... substrate."

The key point of SWCNT ... parent SWCNTs. Through ... characterization the tean ... same structure.

According to Zhang, the ... catalysts for the growth o...

"Firstly, it can not congre... congregate at high tempe... carbon radicals will direc... the same structure as th... structures might act as a...

By Michael Berger. Copy...

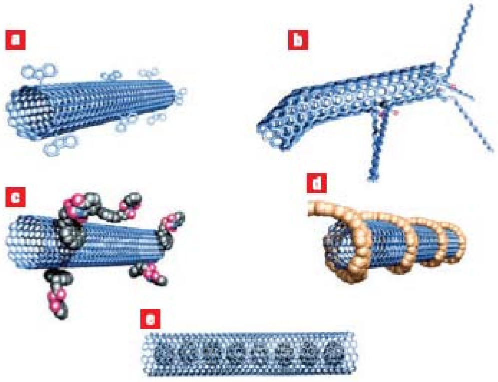


Control of metallic-/semiconducting- of SWNTs

—— UV irradiation assistance CVD growth

Separation of s-SWNTS and m-SWNTs after growth

Functionalization



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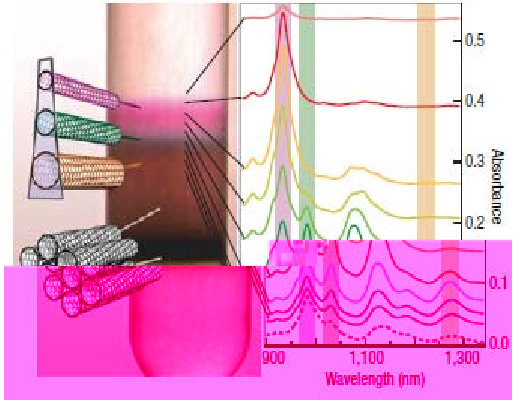
density gradient ultracentrifugation

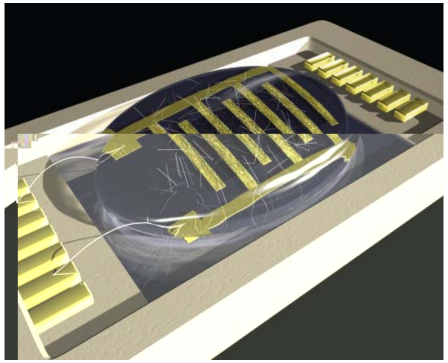


M. S. Arnold, Nature Nanotech. , 2006

Ion-exchange chromatography

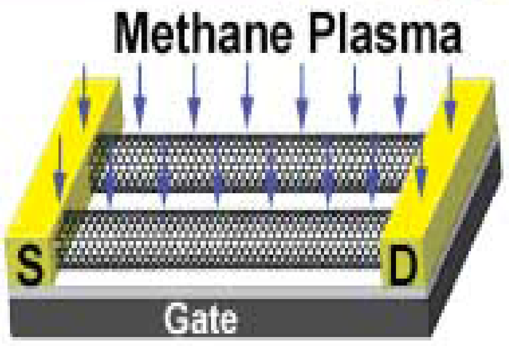
M. Zheng, Nature Mater., *2003*

alternating current dielectrophoresis



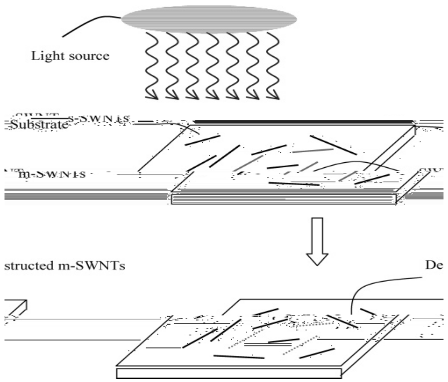
R. Krupke. Science, 2003

gas-phase plasma hydrocarbonation



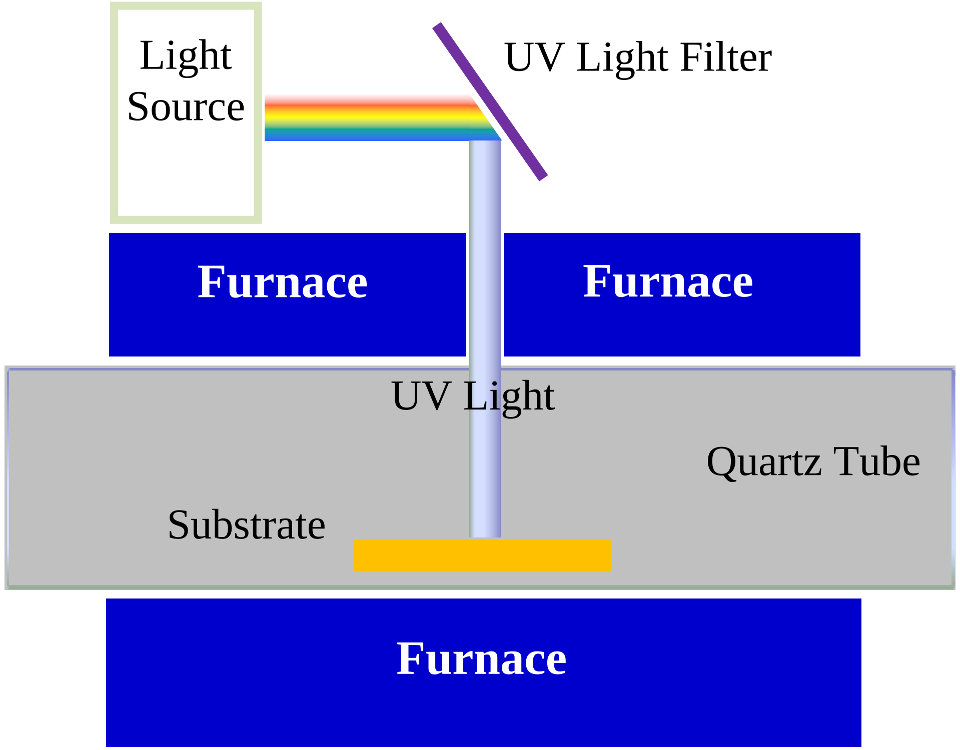
H. J. Dai. Science, 2006

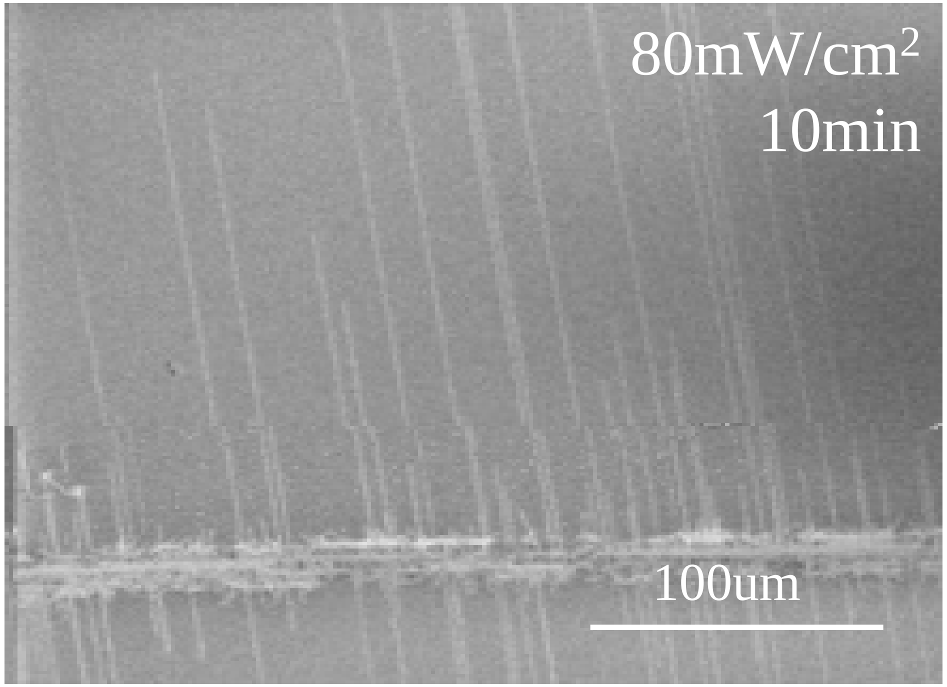
Laser Irradiation



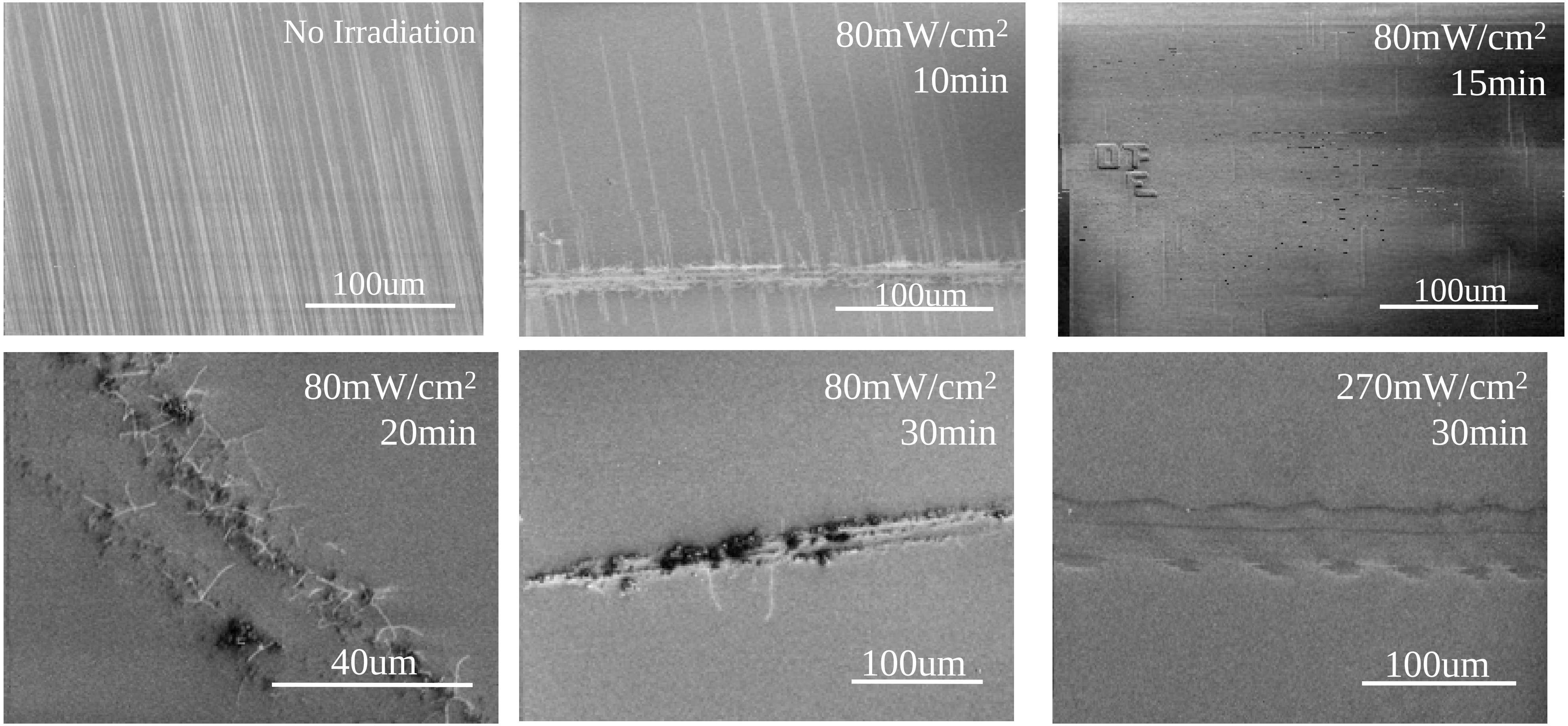
H. J. Huang, J. Phys. Chem. B, 2006

Sketch map of the home-made chemical vapor deposition system

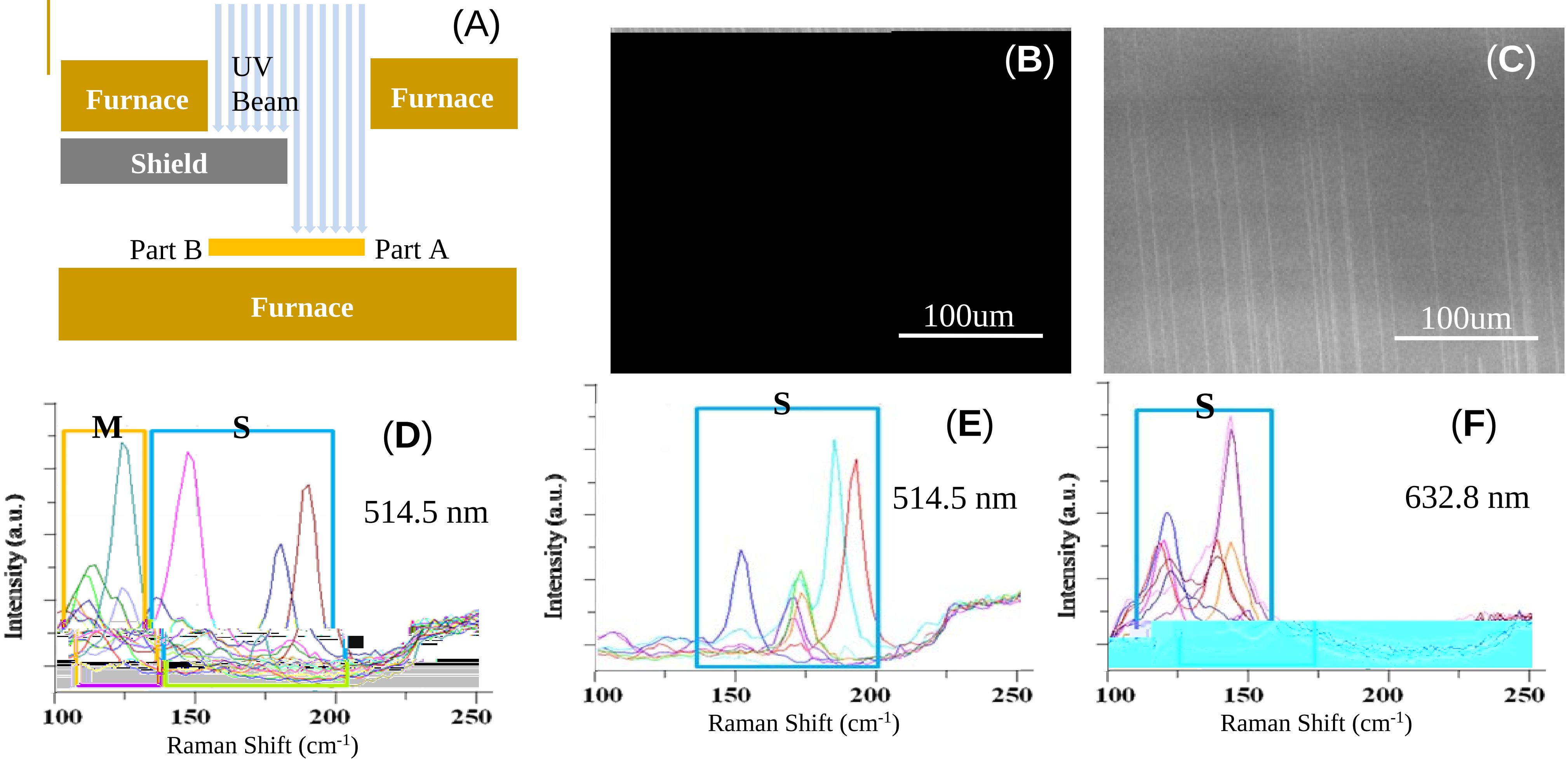




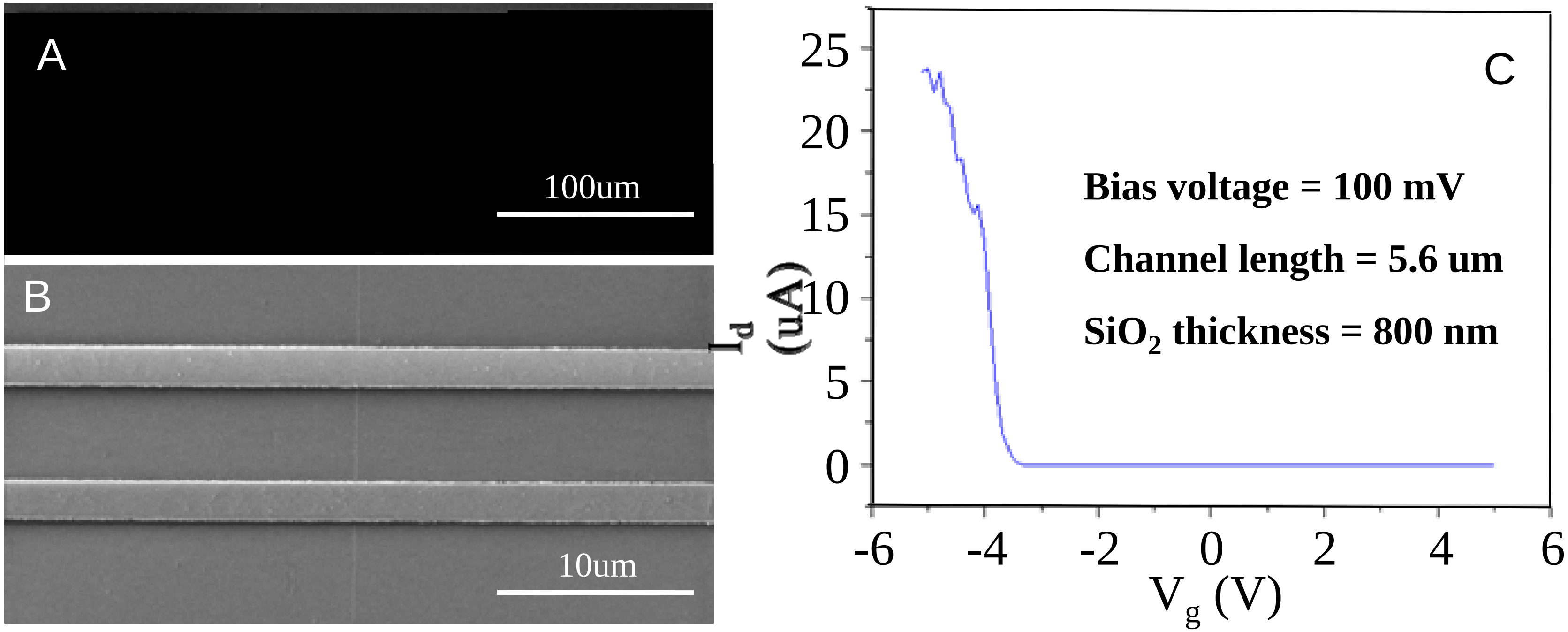
SEM images of SWNTs arrays under different irradiation time



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

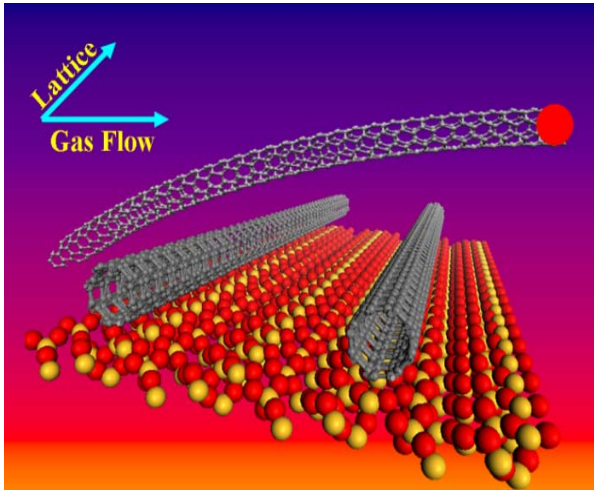


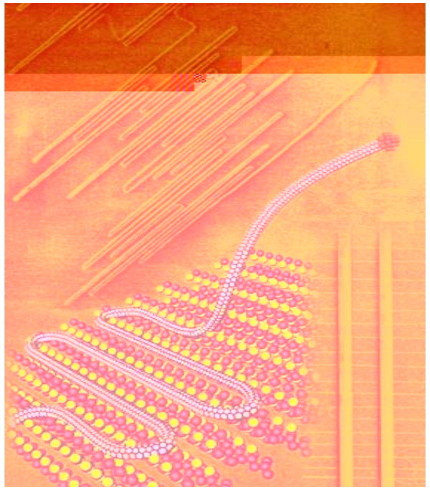
(A) Sketch map of the comparison experiment for SWNT growth with and without UV irradiation. (B)/(C) SEM image of the growth result without/with UV irradiation. (D) Raman spectrum for part B with 514.5 nm excitation. (E)/(F) Raman spectrum for part A with 514.5/632.8 nm excitation. The metallic SWNTs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



The Raman spectra demonstrated an amazing result that almost 100% SWNTs were semiconducting ones. To further confirm the percentage of the semiconducting SWNTs in this sample, we performed electrical measurement in the single-tube field effect transistors (FET) form. Figure A and B were the low and high magnified SEM images of the single-tube FET structure. Fig. C was the typical I-V curve of a semiconducting SWNT with the on/off ratio over 10^4. The test parameters of the electrical measurement were inserted in Fig. C. The bias voltage was 100 mV, the channel length was 5.6 um, and the SiO2 thickness was 800 nm. The electrical measurement data showed that 21 out of 22 SWNTs were semiconducting ones.

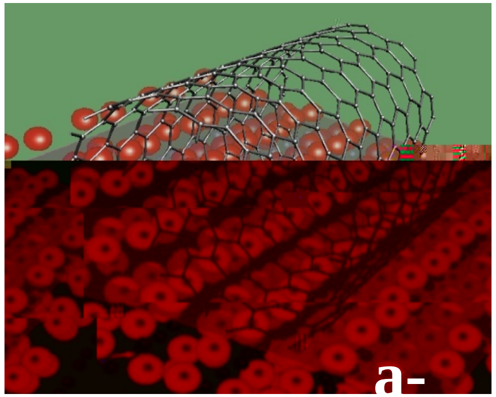
J. Zhang et al., J. Am. Chem. Soc., 2009, In press

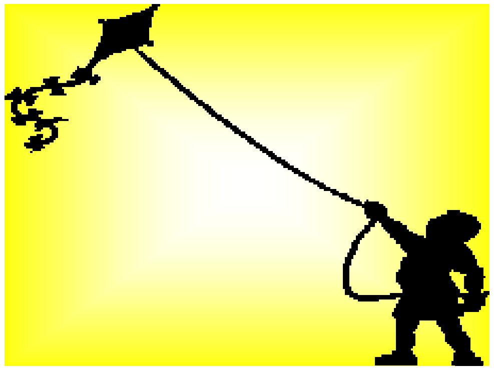


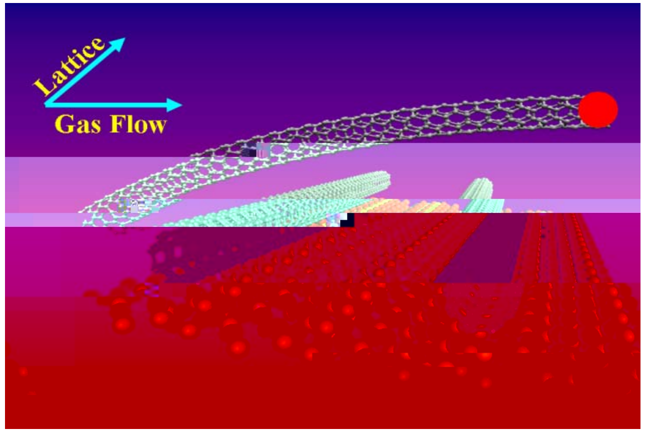


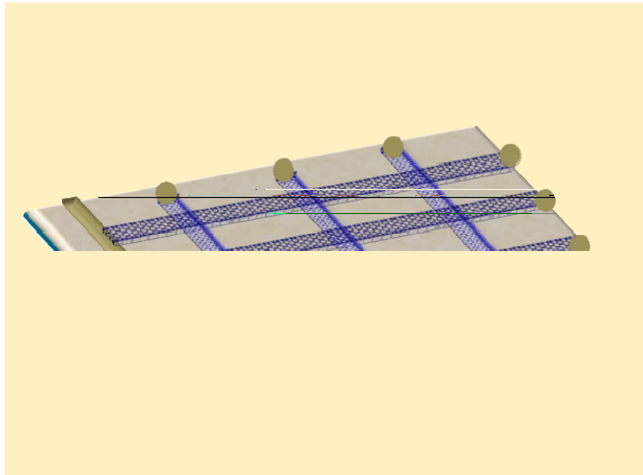
Control of local conformation and architectures

—— Cooperative growth of floating and lattice oriented growth modes

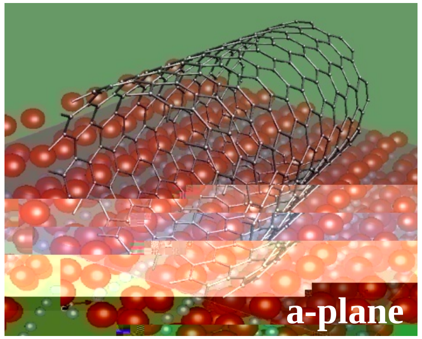

a-



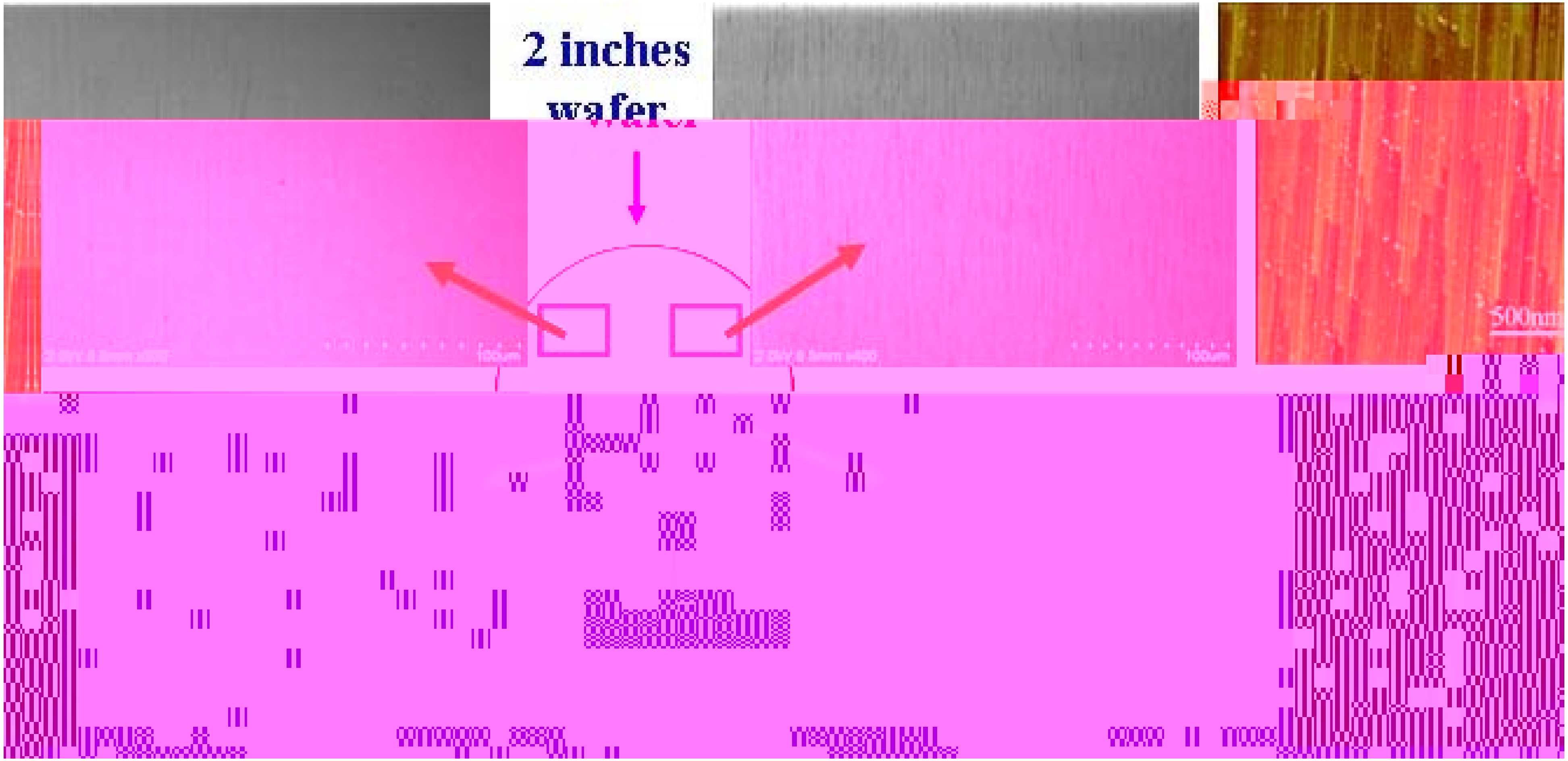

Lattice
Gas Flow



High Density SWNTs Array on Surface

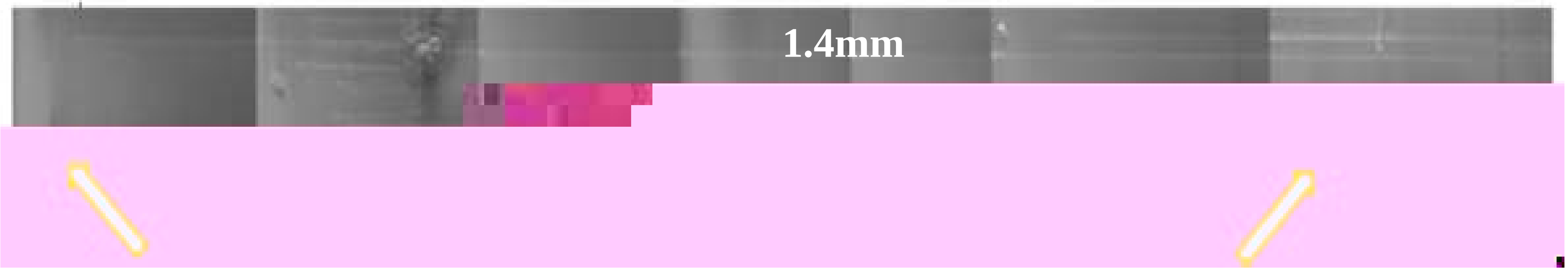


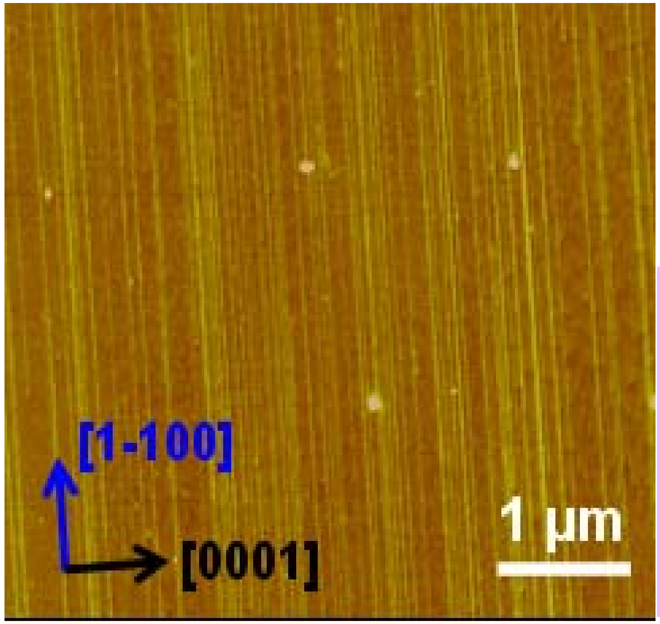
High Density SWNTs Arrays on 2 Inches Wafer

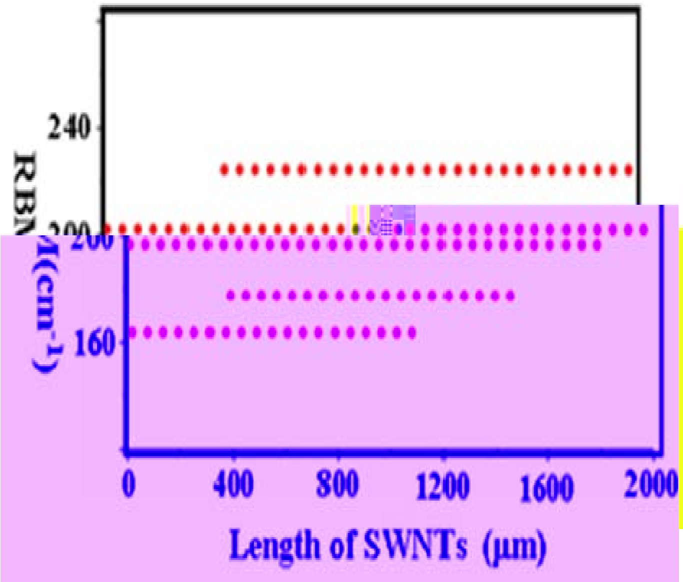


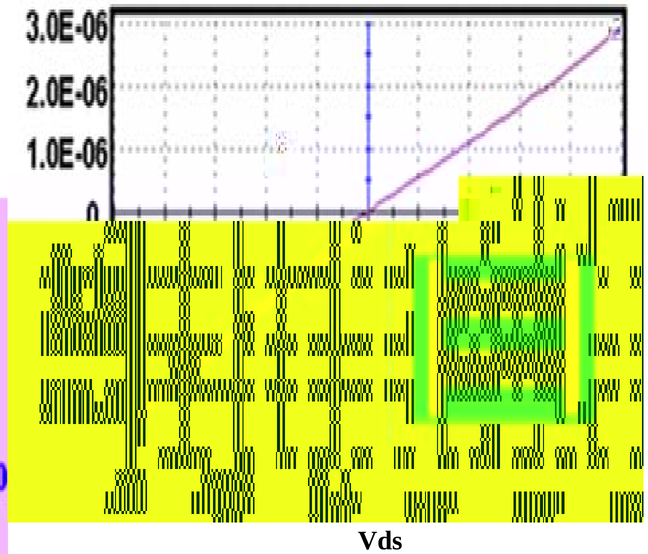
The Density is about 35- 40 tubes per micrometer

The length of the High Density SWNTs

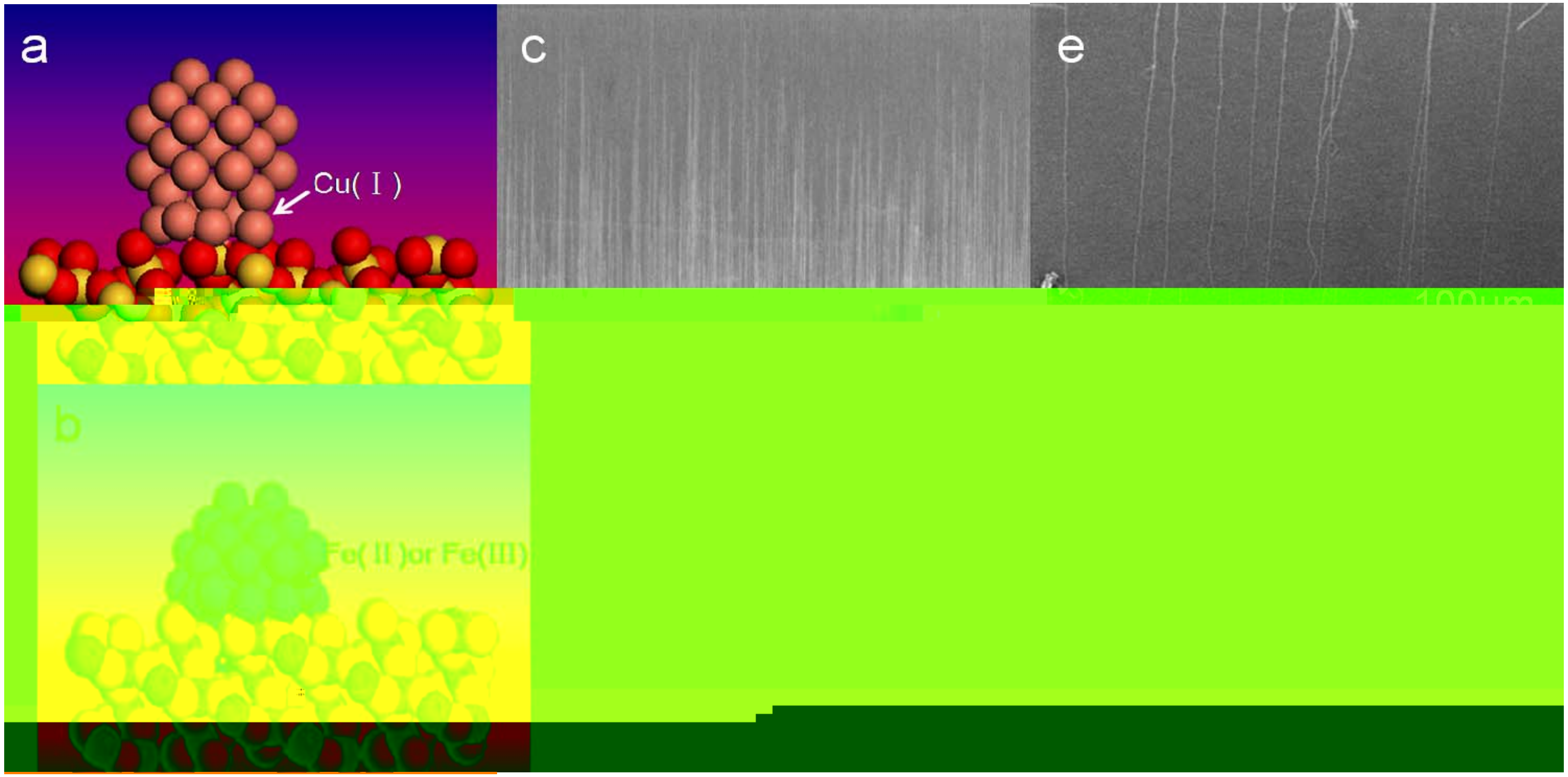








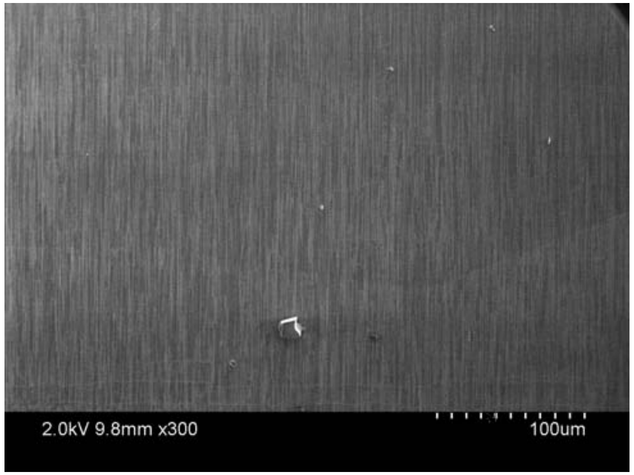
Interaction between Cu, Fe Catlysts and Quartz Surface



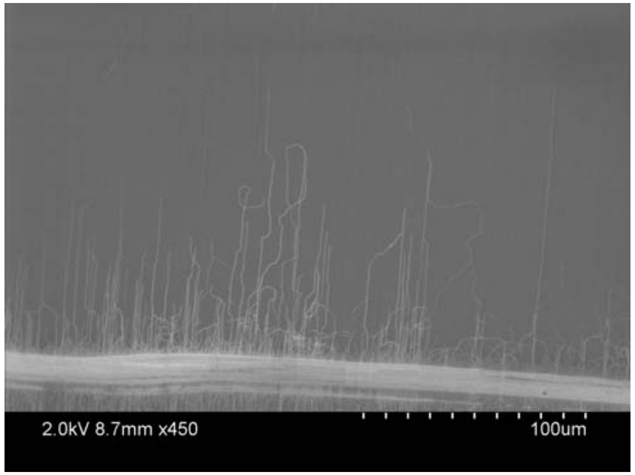
a) and b) illustrate the interaction between Cu, Fe nanoparticles and surface of quartz, the red balls represent oxygen atoms. c) and d) High-magnification SEM image of the lattice assisted SWNTs catalyzed by Cu and Fe. e) and f) Results of gas flow directed growth of carbon nanotubes where Cu and Fe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

The Effect of Temperature on the Growth of SWNTs on Quartz Surface

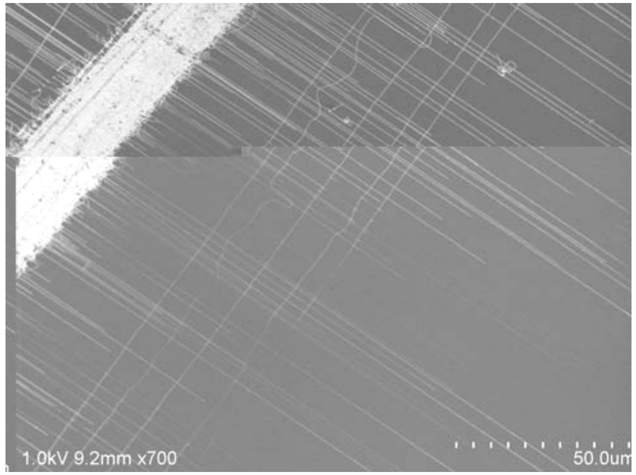
900^{o}C



970^{o}C



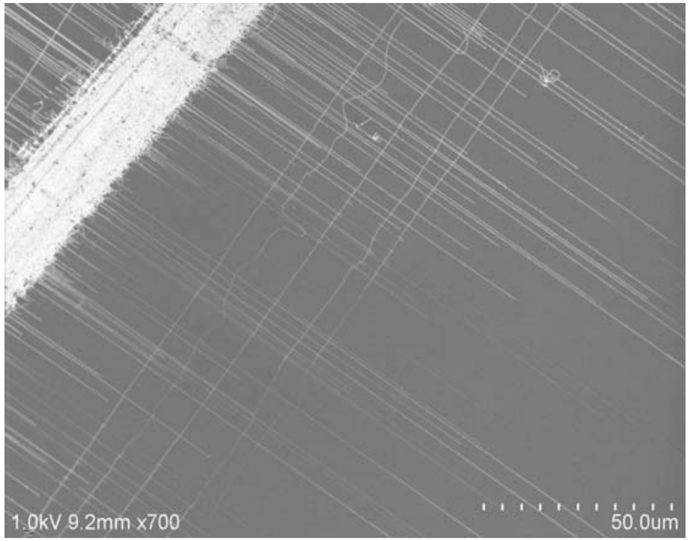
930^{o}C

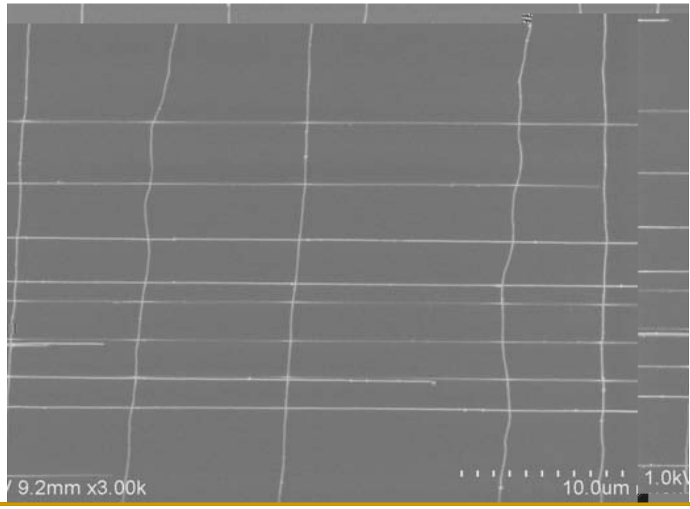


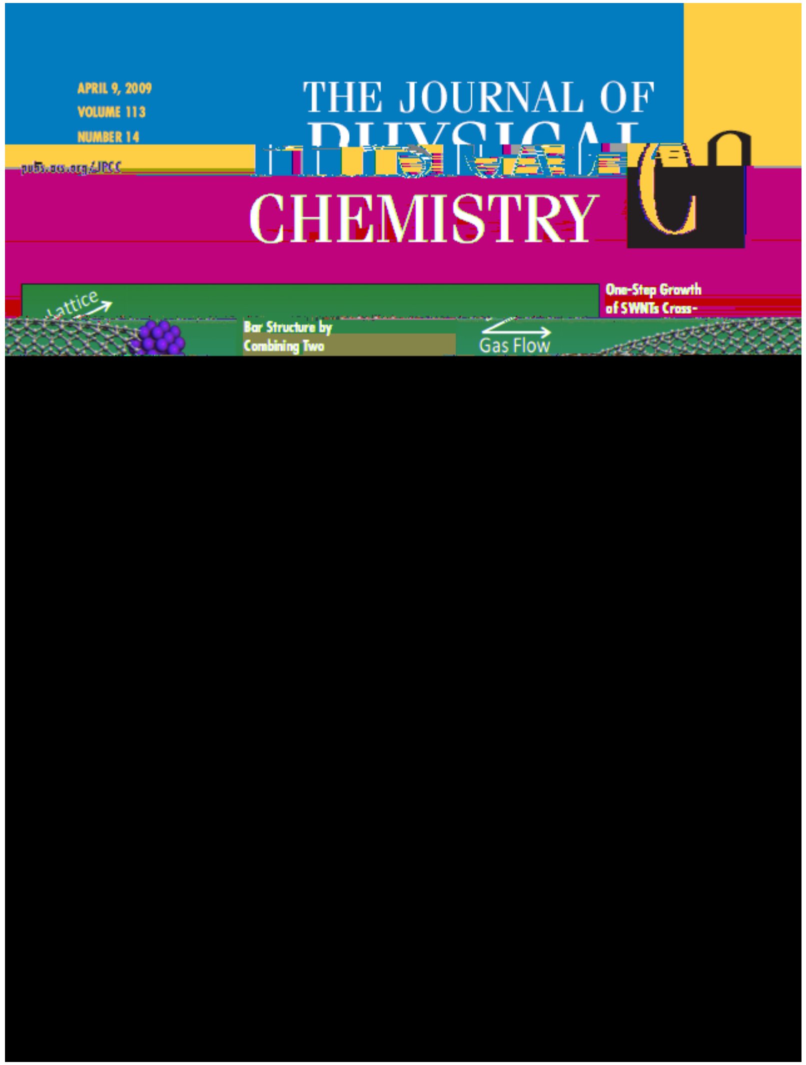
1. low temperature(900): high density of lattice directed carbon nanotubes, few gas flow directed carbon nanotubes
2. optimized temperature(930-950): the density of lattice directed carbon nanotubes is acceptable and it is possible for the growth of gas flow directed carbon nanotubes
3. high temperature(970): lattice will be damaged by such high temperature

SWNTs Crossbar 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.

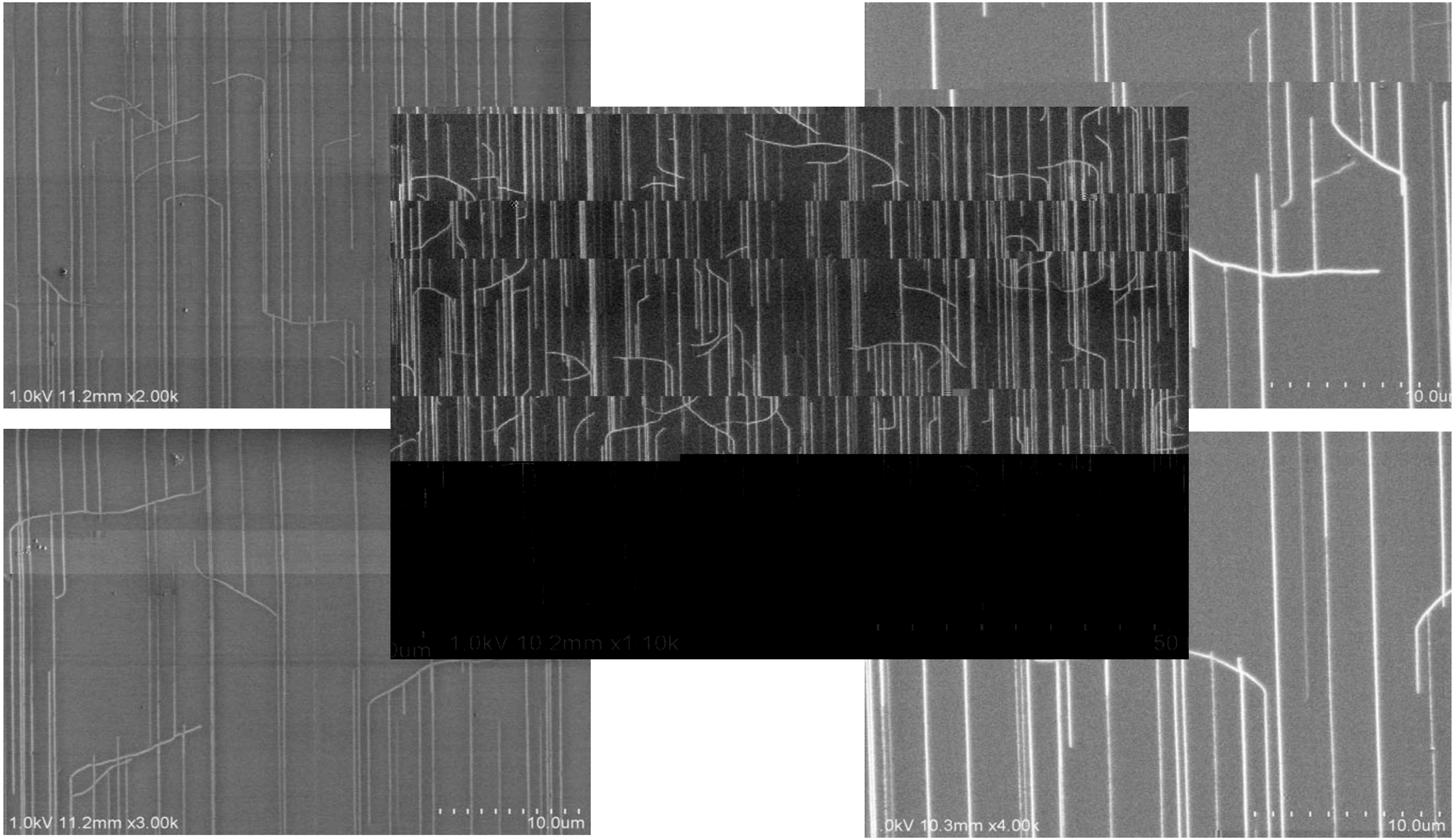


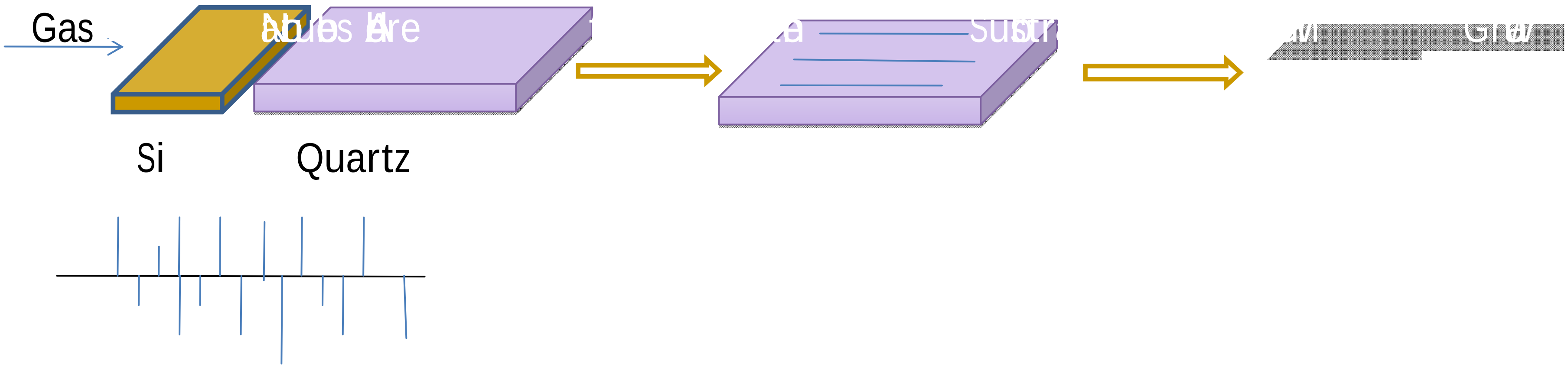


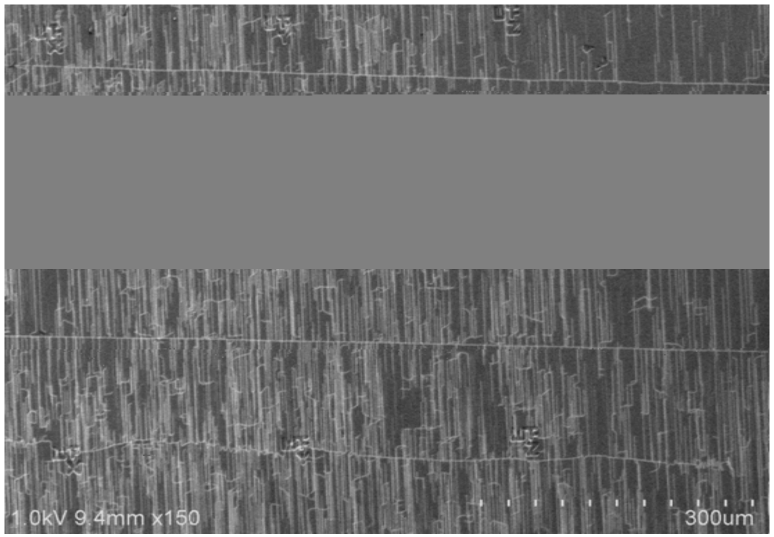


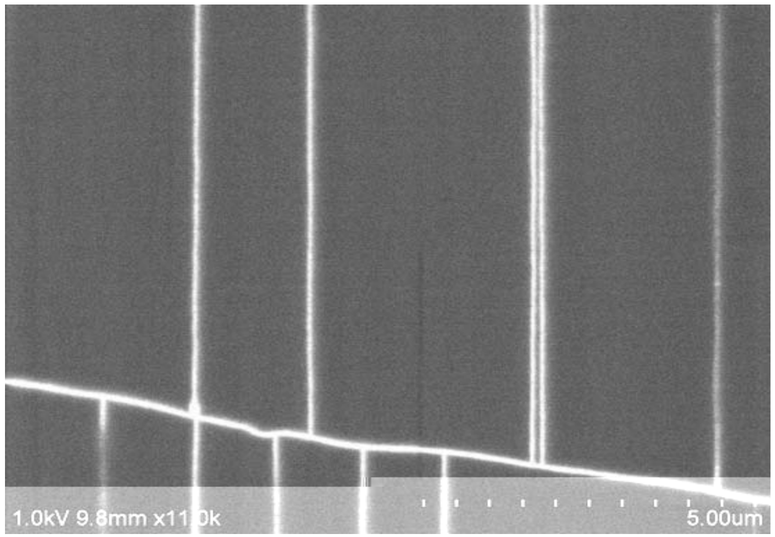
J. Zhang et. al., J. Phys. Chem. C. 2009, 113, 5341-5344 (cover)

The Phenomenon of the Experiment

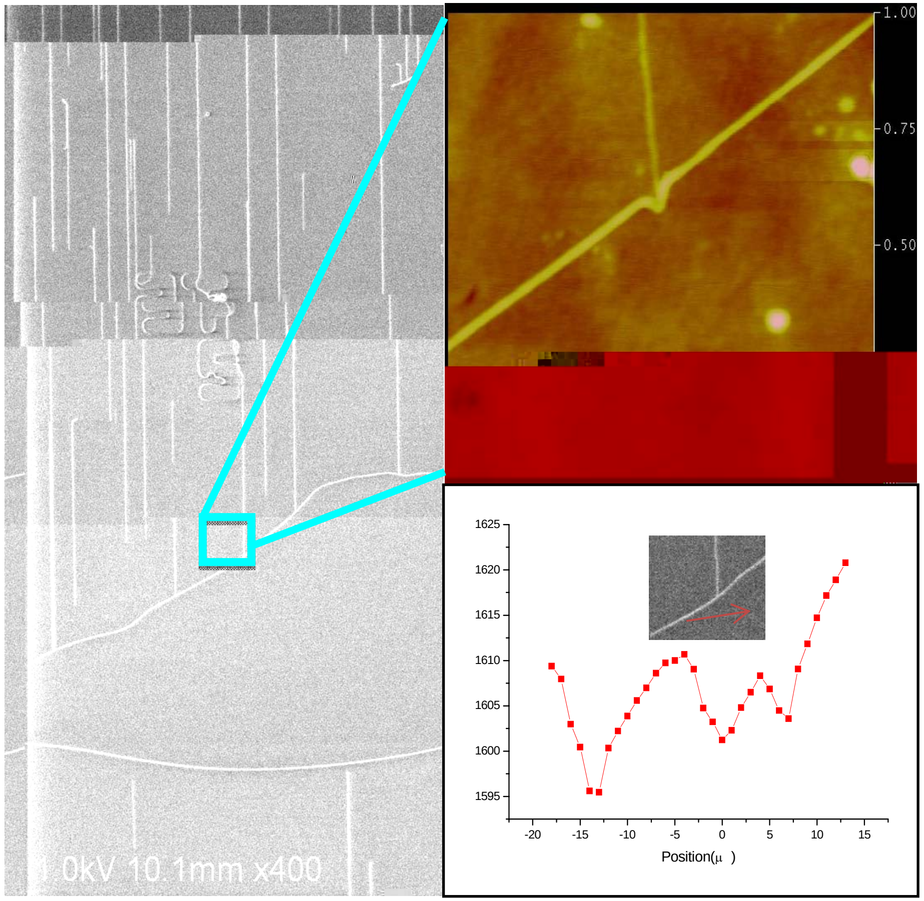


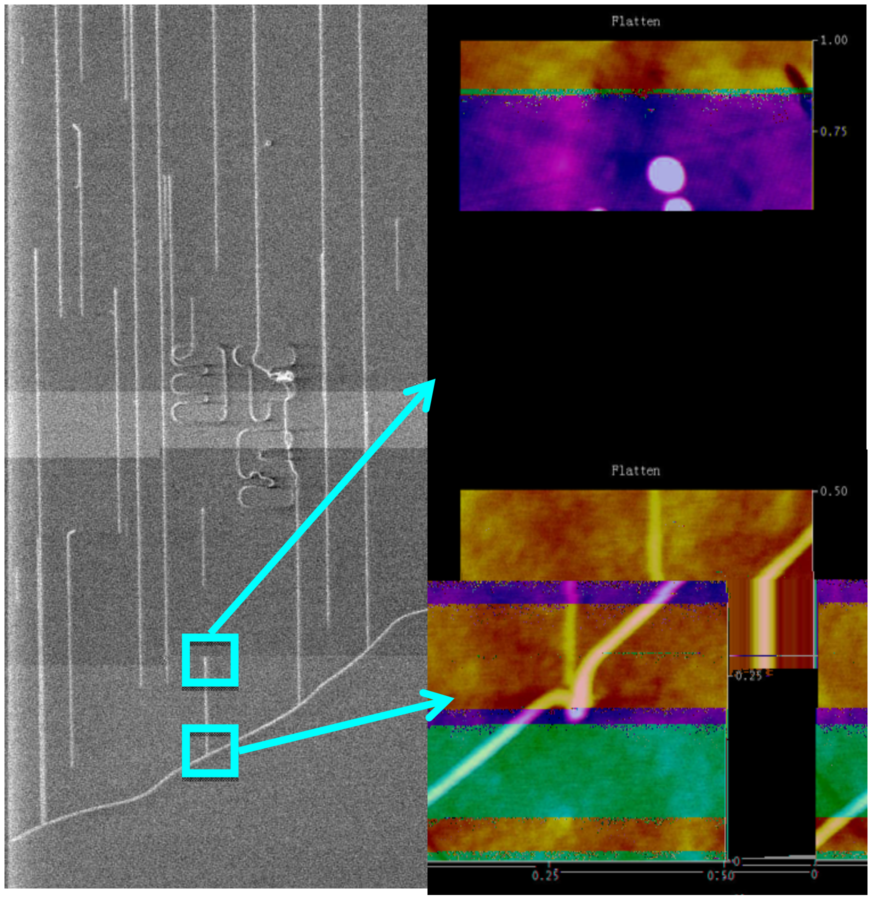

Gas
Si
Quartz


1.0kV 9.4mm x150
300um


5.00um

SEM　AFM & Raman Results

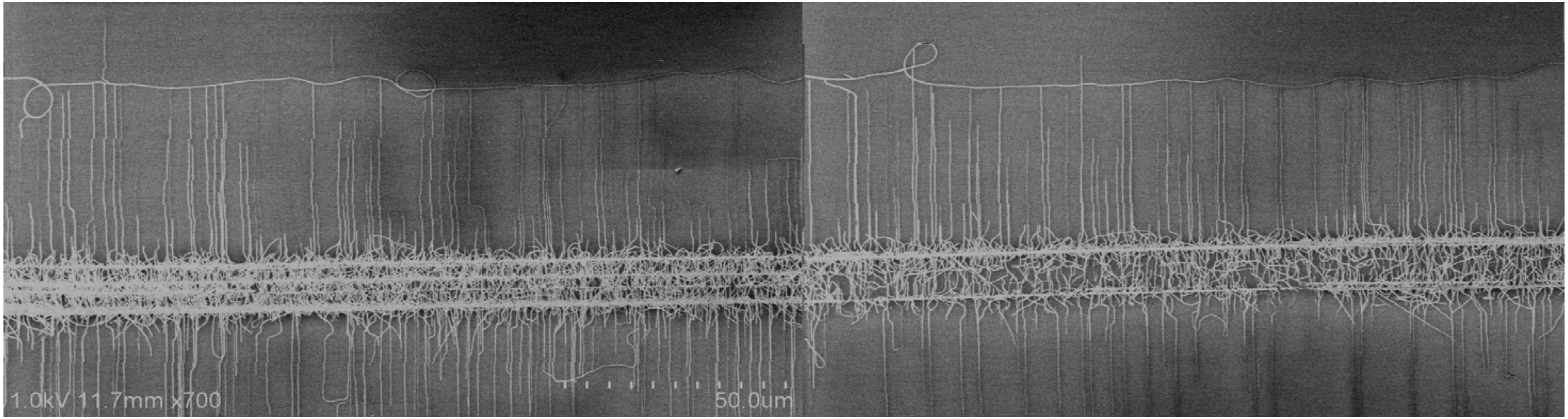


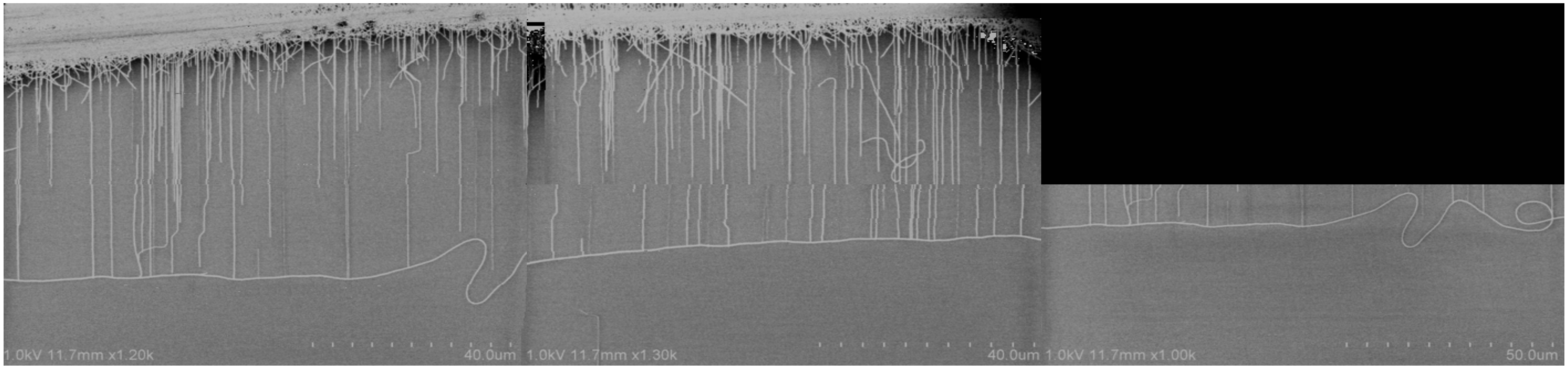


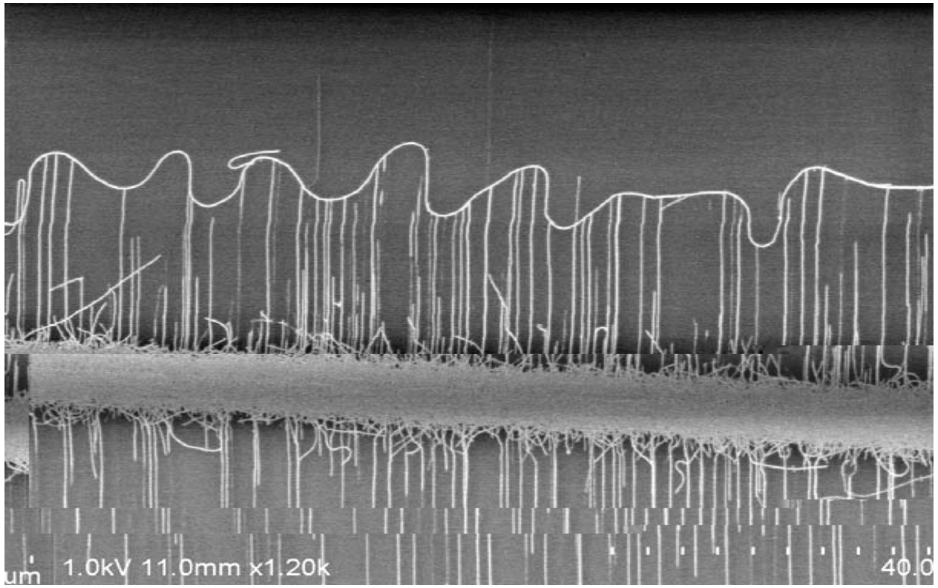
One carbon nanotube hit against another one.

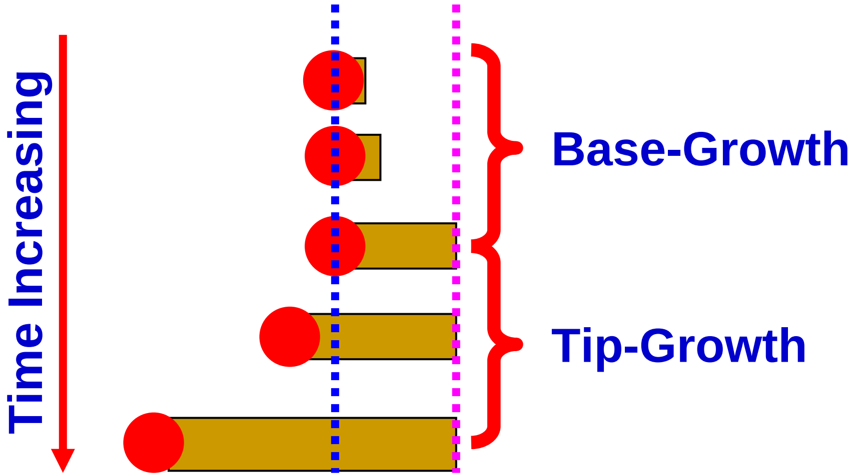
Base-growth Mechanism

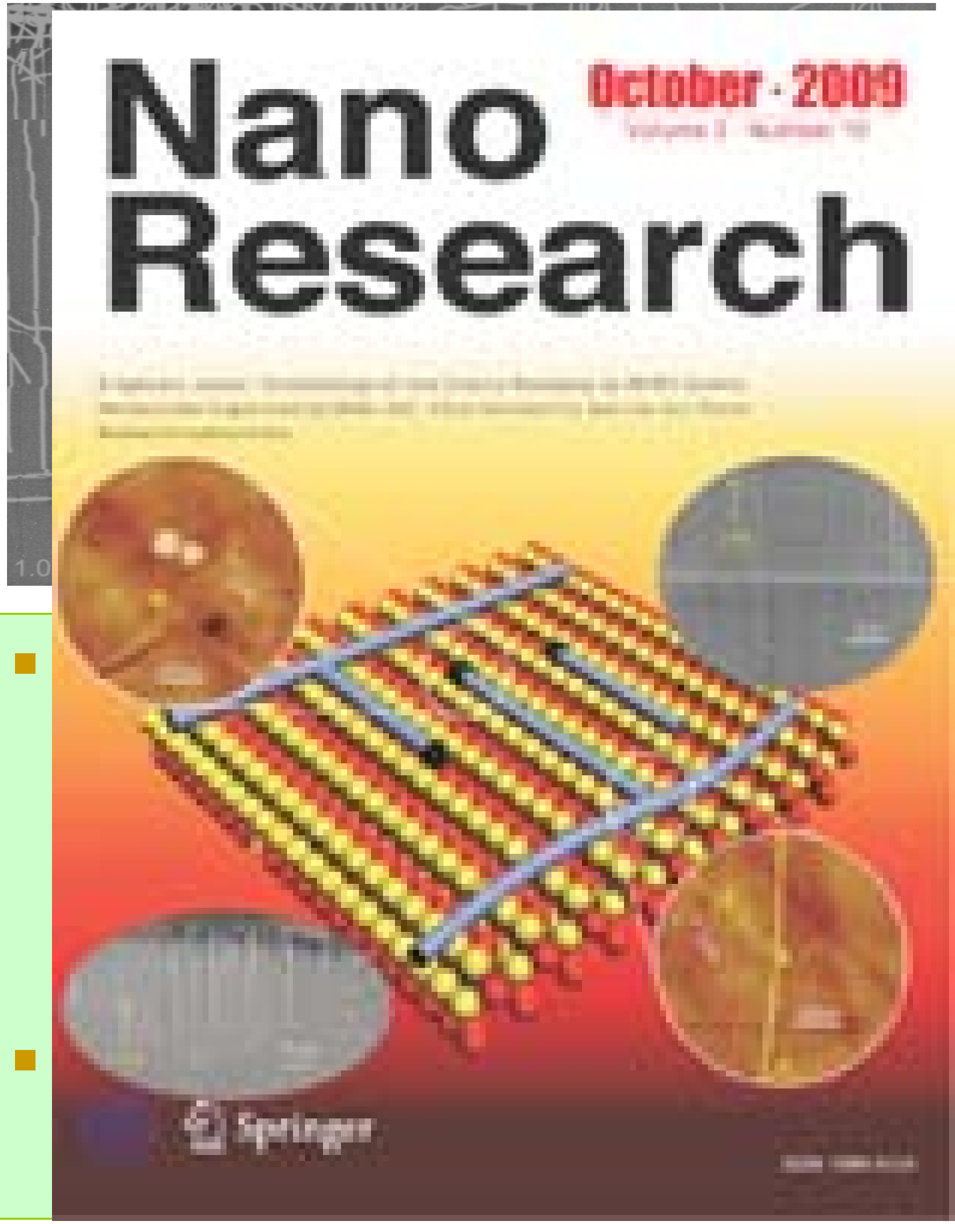
Length-controlled Growth of SWCNTs







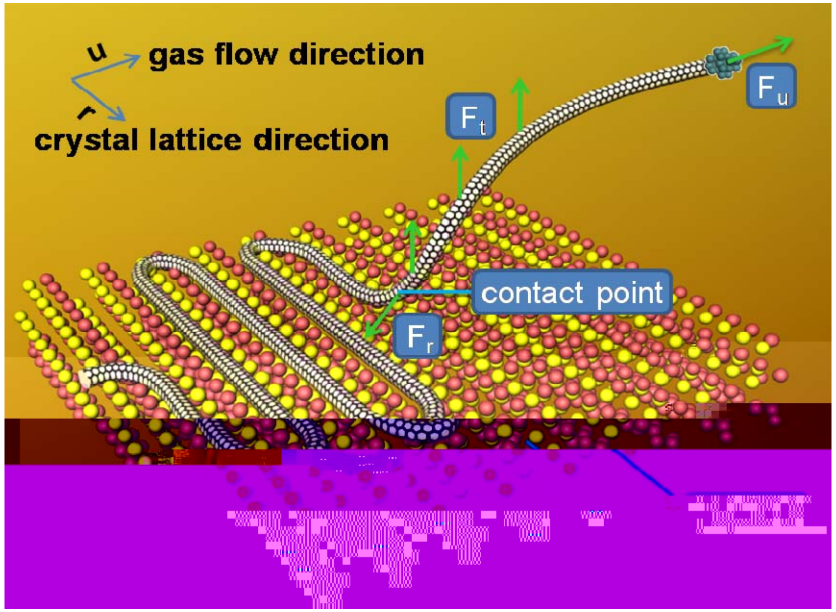




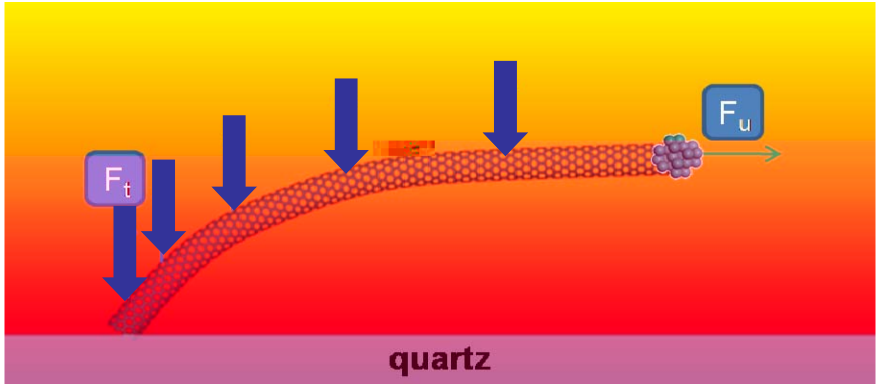
Growth Mode of SWNTs on Quartz

J. Zhang et al., Nano Research., 2009, 2(10),768-773.(Cover paper)

Control of Local Conformation



Cooling down process



Cooperation of floating and lattice-oriented modes

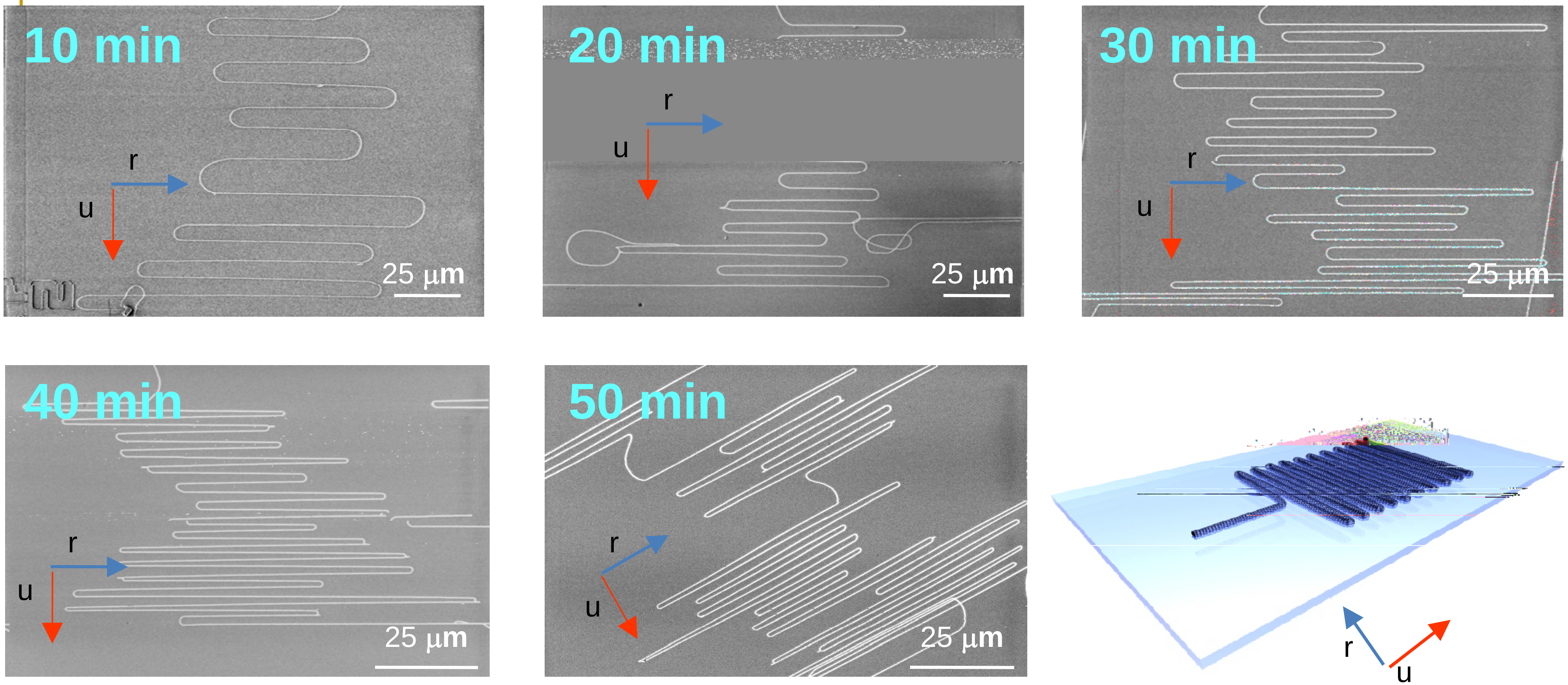
- **Shear friction force (F_u)**
- **Thermal buoyancy force (F_t)**
- **Lattice-alignment force (F_r)**

(1) Activate the floating mode by growing at high temperature (975°C);

(2) Stop the growth and switch to cooling process;

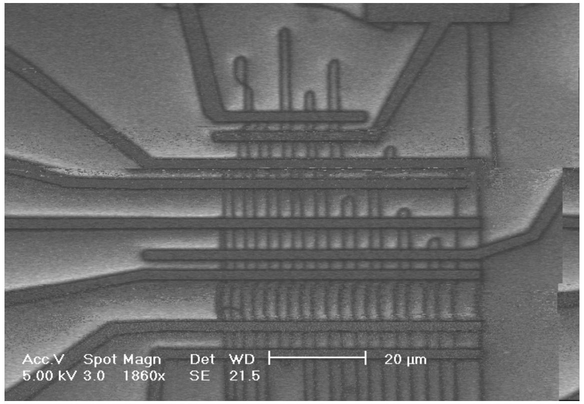
(3) Activate the lattice-oriented mode by slowing down the falling speed.

J. Zhang et al., Adv. Mater., 2009, in press (Inside Front Cover)

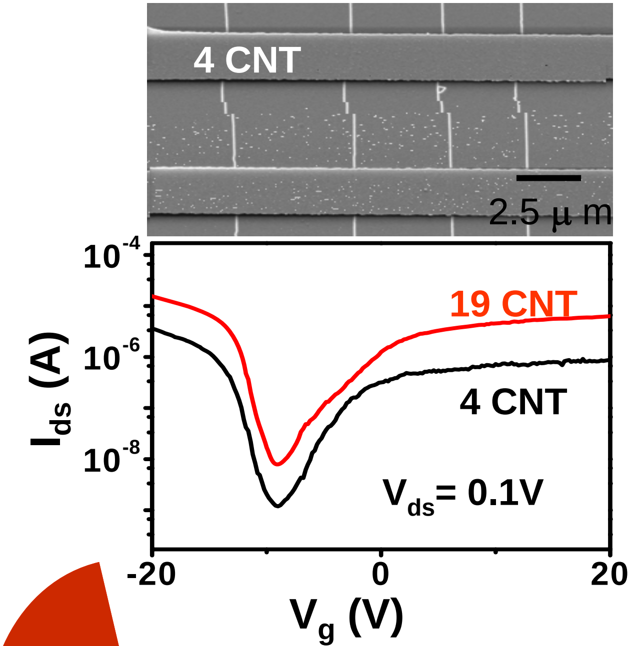


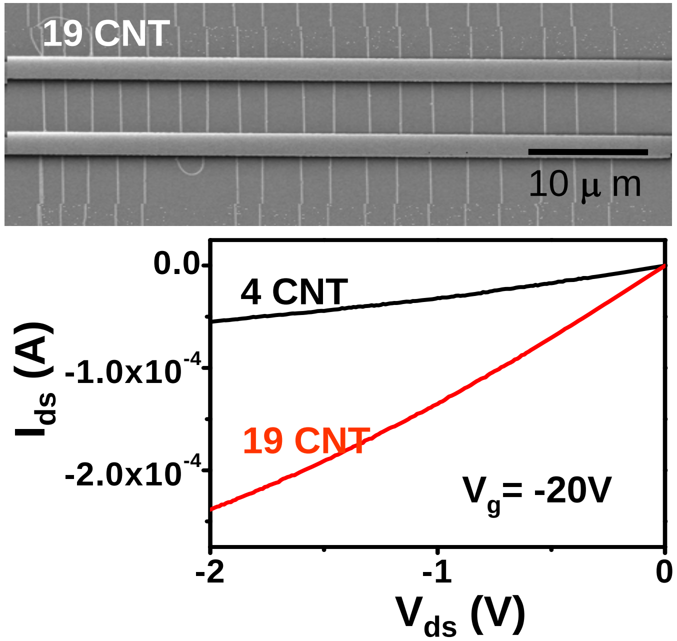
When setting gas flow direction perpendicular to the lattice orienting direction and cooling down the system from 975°C to 775°C at low speed (4-20°C/min), we found that, the slower the cooling speed, the higher the tube packing density.

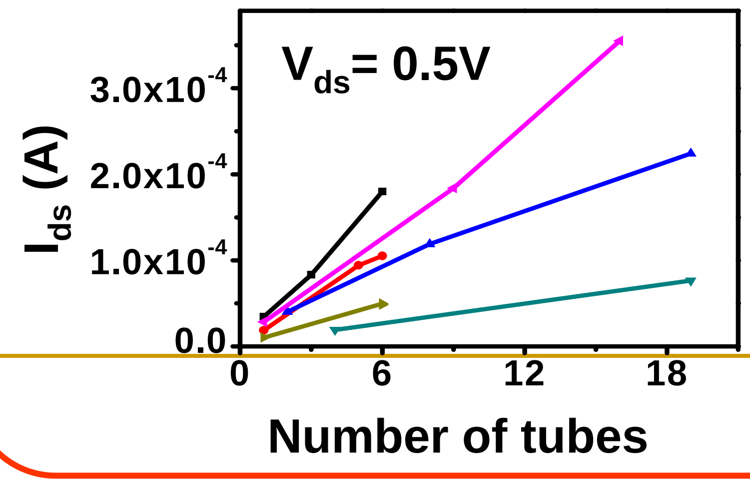
High Performance SWNT-FET with Identical Chirality



Pd electrode, 800nm SiO_2 gate dielectric







Summary

Single-Walled Carbon Nanotubes

↓

Application the SWNTs in Future Devices

↓

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.


Thank Yo