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How Catalysts Affect the Growth of Single-Walled Carbon Nanotubes on Substrates

By *Yan Li,* Rongli Cui, Lei Ding, Yu Liu, Weiwei Zhou, Yan Zhang, Zhong Jin, Fei Peng,* and *Jie Liu**

Direct growth of single-walled carbon nanotubes (SWNTs) on flat substrates by chemical vapor deposition (CVD) is very important for the application of SWNTs in nanodevices. In the growth process, catalysts play an important role in controlling the structure of SWNTs. Over the years, we have systematically studied the size-controlled synthesis of Fe-based nanoparticles and the CVD growth of SWNTs, especially the horizontally aligned SWNTs, catalyzed by these produced nanoparticles. Some new catalysts were also developed. Among them, Cu is shown to be a superior catalyst for growing SWNT arrays on both silicon and quartz substrates and Pb is a unique catalyst from which one can obtain SWNTs without any metallic contaminant. SWNTs prepared with both Cu and Pb are very suitable for building high-performance nanodevices. These studies are also very helpful for further understanding the growth mechanism of SWNTs.

1. Introduction

Even though structures of carbon nanotubes have been observed before,[1,2] it is the publications from Iijima and co-workers on the structure of multiwalled carbon nanotubes (MWNTs) in 1991 and single-walled carbon nanotubes (SWNTs) in 1993[3] that attracted the attention of the research society. Since then, SWNTs have been one of the most intensively studied materials because of their unique electronic, optoelectronic, and mechanical properties.[4] A SWNT can be seen as a cylinder formed by rolling up a piece of graphite sheet. The properties of SWNTs highly depend on their structure. The applications of SWNTs have also attracted great attention. The SWNT is expected to be one of the alternative materials of silicon for future nanoelectronics.[5,6] The reliable production of SWNTs of high purity and controlled property is essential for the future success of carbon-nanotube-based electronics. SWNTs need to be deposited on proper substrates for building nanodevices. However, before being positioned onto the substrates, the bulk-form SWNTs need to be purified and dispersed into solution. Thus, damage and contaminants are possibly introduced on the SWNTs, and their presence will degrade the performance of SWNT-based nanodevices. SWNTs directly growing on substrates are immediately ready for nanodevice building, avoiding the disadvantages of bulk-form SWNTs. Therefore, study on the direct growth of SWNTs on flat substrates is very important.

Chemical vapor deposition (CVD) is the most common method used to prepare SWNTs on substrates. It is generally accepted that SWNTs grow through a vapor–liquid–solid (VLS) mechanism (Scheme 1) and the catalyst nanoparticles play very important roles in the decomposition of the carbon source (CH_4, CO, CH_3CH_2OH, C_2H_4, etc.) and the initiation of the growth of SWNTs.[7] Therefore the quality and structure of the produced SWNTs strongly depend on the types and properties of the catalysts used. The study of catalysts for CVD growth of SWNTs is of great importance in producing high-quality SWNTs, understanding the formation mechanisms, and achieving desired control over the structure of SWNTs. In this Research News, we summarize our research over the last decade on catalysts for CVD growth of SWNTs on flat substrates.

2. Fe and Fe–Mo Alloy: The Most Widely Used Catalysts

From the very beginning of the CVD growth of SWNTs, Fe- and Mo-based catalysts were used in the process.[8–11] They have also been very successful in growing SWNTs on flat substrates.[12–15] For the growth of SWNTs, metallic nanoparticles of Fe and Fe–Mo or their corresponding precursors normally need to be deposited onto the substrates before the CVD process. The size of the catalyst particles is crucial for the preparation of SWNTs. We developed many methods to control the particle size and deposition of iron-containing nanoparticles onto substrates and studied the catalytic CVD growth of SWNTs.

[*] Prof. Y. Li, R. Cui, Y. Liu, Dr. Y. Zhang, Dr. Z. Jin, F. Peng
Beijing National Laboratory for Molecular Sciences
State Key Laboratory of Rare Earth Materials Chemistry and Applications
Key Laboratory for the Physics and Chemistry of Nanodevices
College of Chemistry and Molecular Engineering
Peking University
Beijing 100871 (P. R. China)
E-mail: yanli@pku.edu.cn
Prof. J. Liu, Dr. L. Ding, Dr. W. Zhou
Department of Chemistry, Duke University
Durham, NC 27708 (USA)
E-mail: j.liu@duke.edu

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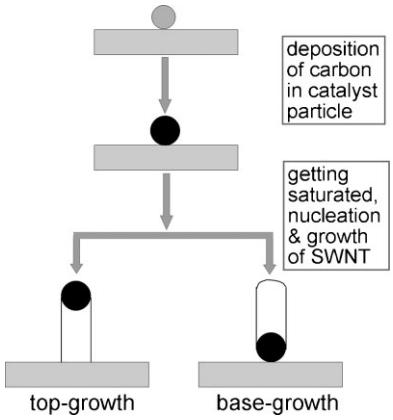


Scheme 1. The vapor–liquid–solid mechanism for the CVD growth of SWNTs.

2.1. The Preparation of Fe and Fe–Mo Nanoparticles with Controlled Size and Narrow Size Distribution

It is generally accepted that the properties of SWNTs are determined by their diameters and helicity. The diameters of the SWNTs, however, highly depend on the size of catalyst particles, as shown in Scheme 1. Using monodispersed nanoparticles with the proper size as catalysts might be able to obtain SWNTs with uniform diameters. There are many strategies developed for the synthesis of uniform metal nanoparticles for nanotube synthesis. Here we summarize some of the common approaches.

Inversed micelles formed by didodecyldimethylammonium bromide (DDAB) in toluene can be used as microreactors to prepare Fe–Mo nanoparticles by reducing $FeCl_3$ and $(NH_4)_2MO_4$ with $LiBH_4$.[16] The size of the produced nanoparticles ranges from 2 to 3 nm, which is suitable for using as catalysts to grow SWNTs.

The thermal decomposition of iron and molybdenum carbonyl complexes using long-chain amine and long-chain carboxylic acid as capping agents is shown to be a very feasible method to obtain monodispersed Fe–Mo nanoparticles with tunable size.[12,17] By varying the reaction time and precursor concentration, especially the amount and the ratio of carboxylic acid and amine, the sizes of the produced Fe–Mo nanoparticles can be tuned between 3 to 14 nm with a stand deviation not exceeding 8%. Figure 1A presents the transmission electron microscopy (TEM) image of Fe–Mo nanoparticles with an average size of ~4 nm obtained by thermal decomposition of their corresponding carbonyl complexes at ~287 °C using octanoic acid and bis-2-ethylhexylamine as capping agents.

Though many strategies have been developed to control the size of the catalyst nanoparticles, it is still a big challenge to obtain nanoparticles of identical size. However, a special kind of inorganic cluster, namely, huge molecular clusters based on transition metals, was obtained as an alternative choice. Each kind of molecular cluster based on a transition metal has fixed diameter because they are molecules with fixed structures. For example, $[H_x\text{-}PMo_{12}O_{40}\subset H_4Mo^{VI}{}_{72}Fe^{III}{}_{30}(CH_3COO)_{15}O_{254}(H_2O)_{98}]\cdot 60H_2O$ is a kind of molecular cluster containing Fe and Mo with identical size of 2.3 nm. Using the nanoclusters as catalyst precursors, SWNTs with very narrow diameter distribution of 1.0 ± 0.18 nm were obtained.[15] What is more significant is that such molecular clusters were synthesized through a facile aqueous solution route at ambient conditions,[15] which is much easier than the preparation of Fe–Mo nanoparticles through thermal decomposition of carbonyl compounds.[12] This research shows that nanoscaled molecular clusters of identical size are superior precursors to obtain monodispersed catalyst nanoparticles that result in SWNTs with uniform diameters.

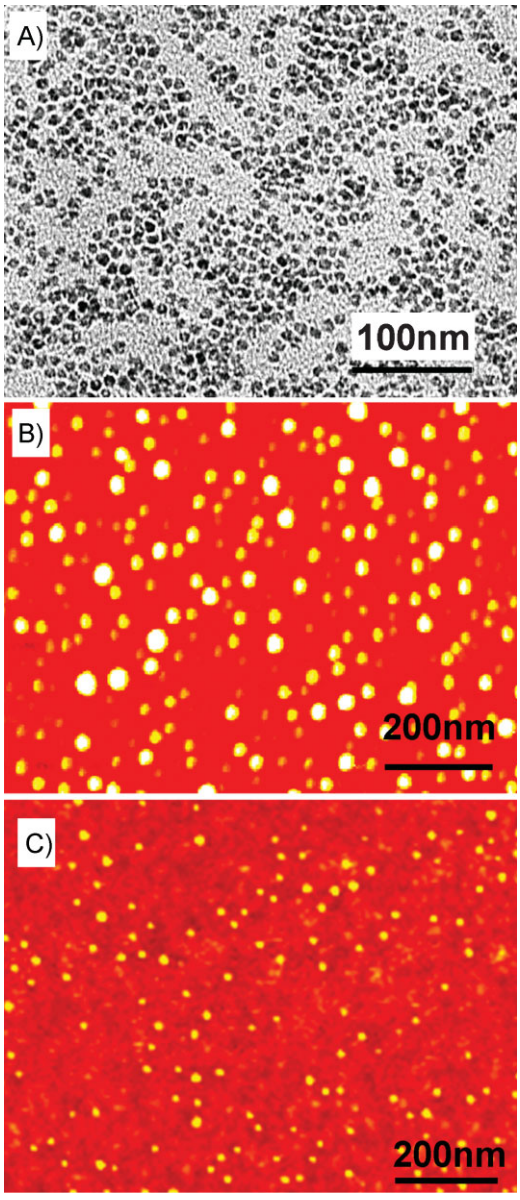


Figure 1. A) Transmission electron microscopy (TEM) image of Fe–Mo nanoparticles prepared by decomposition of corresponding carbonyl complexes and using octanoic acid and bis-2-ethylhexylamine as capping agents. B) Tapping-mode atomic force microscopy (AFM) image of $Fe_2O_3\cdot n\,H_2O$ nanoparticles prepared by microcontact printing using an as-prepared PDMS stamp. C) Tapping-mode AFM image of Fe_2O_3 nanoparticles formed on silicon wafer with $FeCl_3$ and the block copolymer.

2.2. Preparation and Deposition of Catalyst Nanoparticles on Substrates

Besides the preparation procedure, the deposition and dispersion of nanoparticles onto substrates is also very important for controlling the final size of the catalyst particles. First, we need to find a solvent in which the prepared nanoparticles can be well-dispersed; then, the surface property should be compatible with the solvent to insure the uniform wetting of the whole substrate; third, it is helpful if there is a surface affinity between the substrate and the nanoparticles. For nanoparticles dispersed in non-polar organic solution, a hydrophobic substrate surface is preferred; for nanoparticles dispersed in aqueous solution, a hydrophilic substrate surface is favorable.

The surface properties of the substrates can be altered by different treatments. The HF-treated silicon substrates are hydrophobic. The piranha solution (3:7 v/v mixed solution of 30% H_2O_2 and concentrated sulfuric acid) or ammonia treated silicon substrates are normally hydrophilic and negatively charged. Surface properties of the substrates can also be modified using different kinds of self-assembled monolayers (SAMs): An alkyl-terminated surface is hydrophobic; An $-NH_2$-terminated surface is positively charged; A –COOH-terminated surface is negatively charged. By dipping the selected substrates in the solution of nanoparticles, by spin coating the nanoparticle solutions on the substrates, or just by dropping the nanoparticle solution onto the substrates, well-dispersed catalyst nanoparticles of proper density can be deposited onto the substrates for CVD processes.

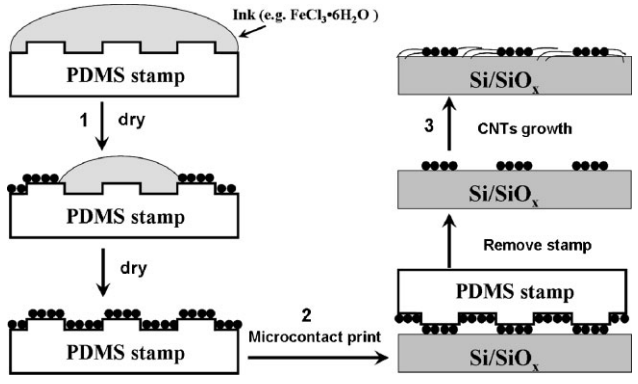
We developed two feasible strategies facilitating both the formation of small nanoparticles of narrow size distribution and the deposition of discrete nanoparticles on target substrates. Microcontact printing (μCP) as a non-expensive soft lithography technique has been widely used to transfer various kinds of materials onto the target substrates forming micro- or nanoscaled features. This technique often employs poly(dimethylsiloxane) (PDMS) as the stamp, which is normally treated with ozone plasma to adjust its surface property. We found that PDMS stamps without ozone oxidization are very suitable to host both the formation and transfer of iron oxide nanoparticles of proper sizes onto substrates for CVD growth of SWNTs (Scheme 2).[18] An ethanol solution of $FeCl_3 \cdot H_2O$ can wet the as-prepared PDMS stamp very well. With the evaporation of ethanol, $Fe_2O_3 \cdot nH_2O$ nanoparticles are formed from hydrolysis. Then these iron oxide nanoparticles are transferred onto the substrates and act as the catalysts for the growth of SWNTs after being reduced. Figure 1B shows the tapping-mode atomic force microscopy (AFM) image of the obtained $Fe_2O_3 \cdot nH_2O$ nanoparticles on a SiO_x/Si substrate.[18]

Polystyrene (53 800)-*block*-poly(2-vinyl-pyridine) (8800) can form micelles with monodispersed size of ~13.3 nm in toluene solution. Therefore, a fixed amount of $FeCl_3$, which can be altered by using $FeCl_3$ aqueous solution of different concentration, can be loaded in the nanometer-sized water pools of the micelles. Then spin coating the solution onto silicon wafer and treating with oxygen plasma will eventually result in discrete uniform Fe_2O_3 nanoparticles with sizes varying from 1.9 to 6.6 nm on substrates.[19] Figure 1C is the tapping-mode AFM image of Fe_2O_3 nanoparticles with a size of ~1.9 nm.

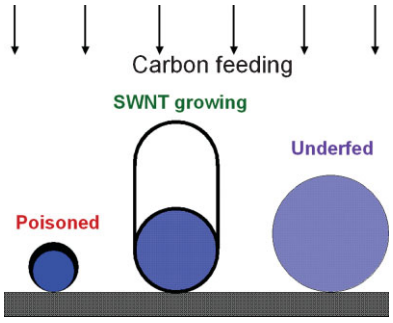
Both of the methods are very flexible, non-expensive, and convenient. The discrete Fe nanoparticles with proper size obtained on substrates are superior for the growth of uniform SWNTs.

2.3. The Growth of SWNTs on Substrates with Fe and Fe–Mo as Catalysts

As mentioned above, the size of the nanoparticles is thought to be one of the key issues for catalyzing SWNTs' growth. It is generally considered that the proper size of nanoparticles for initiating the growth of SWNTs is around 1 nm[18] though the size of the catalyst precursors might be much larger. It is also widely accepted that the diameters of the produced SWNTs are determined by the size of the catalyst nanoparticles.[15] However, the size of nanoparticles tends to change during the CVD process because of the evaporation of metal atoms at high temperature and the dissolving of carbon species in the nanoparticles. Therefore, it is very difficult to define a quantitative relation between the size of the nanoparticles and the diameter of the resultant SWNTs. Nevertheless, our study on the relationship between the carbon feeding rate and the diameters of the produced SWNTs gives a close observation about how the size of the nanoparticles influences the growth of SWNTs.[20] As shown in Scheme 3, at a given carbon feeding rate, only the nanoparticles of the right size can nucleate the SWNTs' growth. The smaller particles are too active and dissolve too much carbon at the beginning. The excess carbon will form a continuous thin layer of graphite covering the surface of the nanoparticle, which will stop further carbon supply to that nanoparticle. Hence, no SWNT can be grown from the smaller particles. The larger nanoparticles cannot efficiently catalyze the decomposition of carbon stocks and, therefore, cannot supply enough carbon to nucleate the SWNTs. Only the nanoparticles of moderate size can ensure a suitable carbon supply for the nucleation and growth of SWNTs. Figure 2A is the scanning electron microscopy (SEM) image of the random SWNT networks grown on SiO_x/Si substrate catalyzed by Fe.



Scheme 2. Schematic illustration of the procedures for the preparation and patterning of $Fe_2O_3 \cdot H_2O$ nanoparticles and the growth of SWNTs on a SiO_x/Si surface [18].



Scheme 3. This scheme shows the relation between the nanoparticle size and carbon feeding rate for the growth of SWNTs. At a given carbon feeding rate, only nanoparticles of the right size are able to nucleate and grow SWNTs [20].

Besides the random SWNT networks, Fe also is shown to be a good catalyst for the growth of horizontally aligned ultralong SWNTs both on SiO_x/Si[14,21,22] and quartz[23] substrates. Because the interaction between carbon nanotubes and amorphous SiO_x substrates is very strong,[24] the orientation of SWNTs cannot be controlled on SiO_x/Si substrates if the nanotubes are grown through base growth. And the lengths of the tubes will be not very large either. Therefore, it is believed that the horizontally aligned ultralong SWNTs are produced via tip growth on SiO_x/Si substrates. The newly grown part of SWNT is floating in the gas flow together with the catalyst nanoparticle above the substrate during the growth process; thus, the orientation of the SWNT is guided by the direction of gas flow. The root part of the tube continuously falls down onto the substrates due to the strong interaction between the SWNT and the SiO_x substrate. This is called the ''kite mechanism'' (Scheme 4). This way, SWNTs as long as several to tens of centimeters can be prepared.[25,26] Figure 2B shows the horizontally aligned ultralong SWNT array grown on SiO_x/Si substrate using Fe as catalyst and methane as carbon source under ultra-low gas flow.[21] Figure 2C shows the dense SWNT arrays grown on quartz substrate using Fe as catalyst and ethanol as carbon source. Here the orientation of the SWNT is determined by the surface lattice of the substrate.[27,28]

3. Cu: A Superior Catalyst for Growing SWNTs on Substrates

Cu was originally thought to be an ineffective catalyst for growing SWNTs.[7] Compared with Fe, Cu has weaker activity in catalyzing the decomposition of carbon stocks and a lower solubility of carbon. This might be the reason why Cu was expected not to be a good catalyst for CVD growth of SWNTs. The decomposition of carbon stocks is necessary to obtain carbon species for the growth of SWNTs. But the very high catalytic activity in carbon stock decomposition actually is a double-edged sword for the growth of SWNTs. The oversupply of carbon could make the catalyst nanoparticles poisoned[20] and also favor the growth of amorphous carbon, MWNTs, and SWNT bundles,[29] and, therefore, is harmful for producing high-quality SWNTs.

Along with the progress in understanding the growth mechanism of SWNTs, we began to realize that copper could

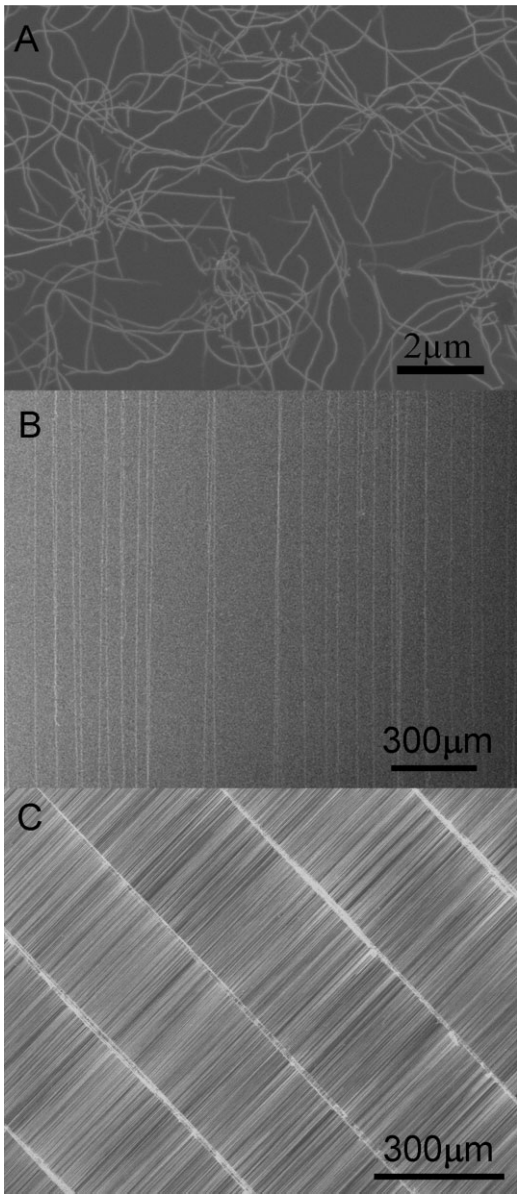
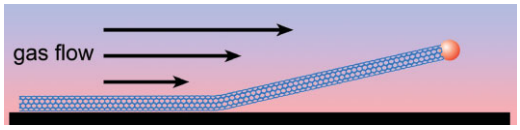


Figure 2. Scanning electron microscopy (SEM) images of SWNTs grown on substrates using Fe as catalyst. A) Random SWNT network grown on SiO_x/Si substrates using methane as carbon source. B) Ultralong SWNT arrays grown on SiO_x/Si substrates using methane as carbon source. C) SWNT arrays grown on quartz using ethanol as carbon source.



Scheme 4. Schematic of the ''kite mechanism'' for the growth of ultralong SWNTs.

be a good catalyst for growing SWNTs on substrates. Cu has some solubility of carbon though much smaller than that of Fe. Thus, it still meets the criterion of acting as the catalyst for the growth of SWNTs through the VLS mechanism. And it may take advantage

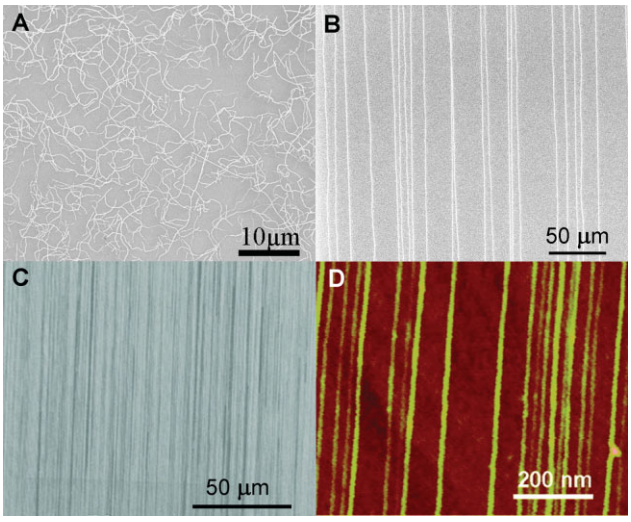


Figure 3. SEM (A–C) and AFM (D) images of SWNTs grown on substrates using Cu as catalyst. A) Random SWNT network grown on a SiO_x/Si substrate using methane as carbon source. B) Ultralong SWNT arrays grown on a SiO_x/Si substrate using methane as carbon source. C,D) SWNT arrays grown on quartz using ethanol as carbon source. C, D) Reproduced with permission from [31]. Copyright 2008, American Chemical Society.

of its weaker catalytic activity in carbon stock decomposition to greatly reduce the chance of forming amorphous carbon and MWNTs. Actually, Cu shows great success in catalyzing the growth of SWNTs on substrates (Fig. 3).[30–33] Cu-catalyzed fast-heating CVD can obtain horizontally aligned arrays of very straight SWNTs on SiO_x/Si substrates (Fig. 3B).[30] Relying on the high efficiency of Cu for the growth of SWNTs, large-area cross-shaped networks of ultralong SWNTs can be prepared by a two-step CVD process.[32] And by modifying the gas flow patterns, curved SWNTs copying the gas flow streamline patterns can also be obtained.[32] On ST-cut quartz substrates, SWNT arrays with density as high as 22 tubes per micrometer (Fig. 3C and D)[31] and pure semiconducting SWNTs[33] were prepared. These results all indicate that Cu is a superior catalyst for the growth of SWNTs on substrates.

Besides the lower catalytic activity for carbon stock decomposition and solubility for carbon, copper also exhibits a weaker interaction with silica than iron.[24,30] Therefore, it is much easier to lift the Cu nanoparticles out of the substrates than Fe nanoparticles. This is an advantage for using Cu as catalyst to grow horizontally aligned SWNT arrays via the ''kite mechanism''. We performed CVD using ethanol as the carbon source and using either Fe–Mo or Cu as catalyst under similar conditions. A network of random SWNTs was obtained from Fe–Mo catalyst (Fig. 4A) and an array of ultralong SWNTs was produced from the Cu catalyst (Fig. 4B).[30]

We also compared the diameter distribution of SWNTs grown from Fe (in Fig. 2A) and those of SWNTs grown from Cu (in Fig. 3A). The diameters were measured by the height profiles of AFM images. The results are shown in Figure 4C and D. For the Cu catalyst, the diameter of the SWNTs ranges from 0.8 to 1.0 nm,

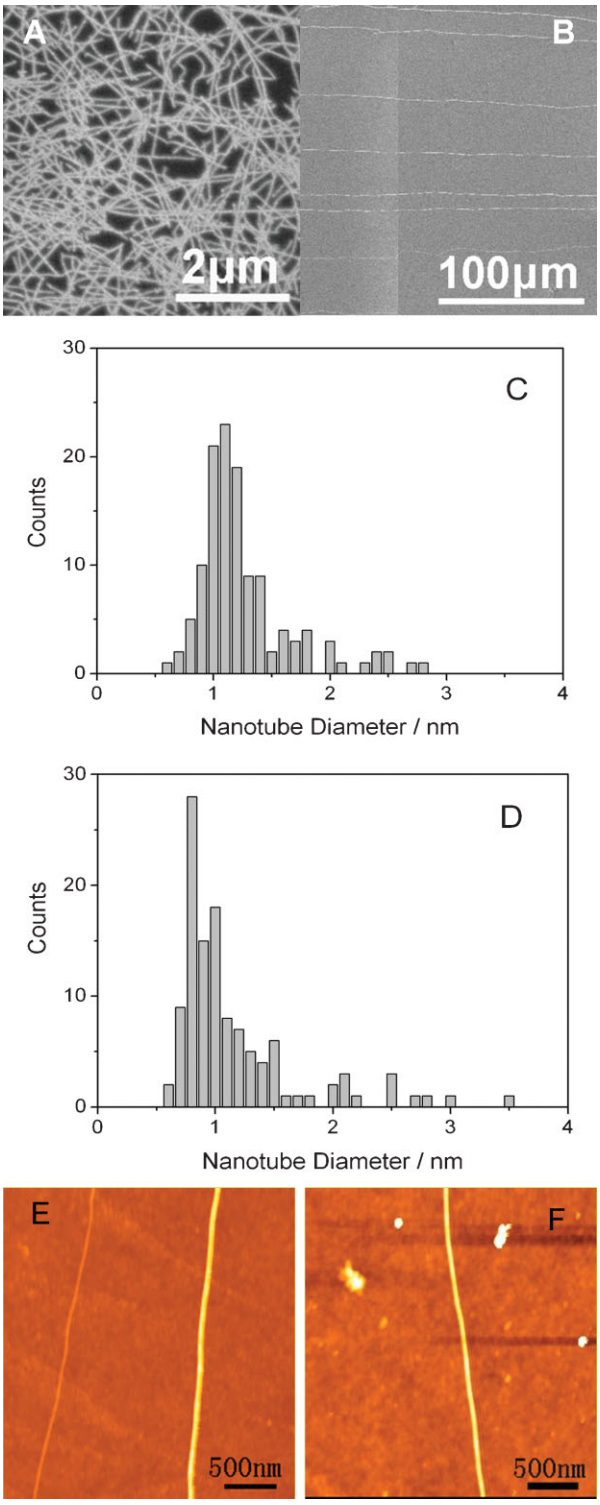


Figure 4. SEM images of random SWNT networks catalyzed by Fe–Mo (A) and ultra-long SWNTs catalyzed by Cu on SiO_x/Si substrates by pyrolysis of ethanol (B). Reproduced with permission from [30]. Copyright 2006, American Chemical Society. C,D) Size distribution analysis from 123 SWNTs prepared with Fe catalyst (C, corresponding to Fig. 2A) and 118 SWNTs prepared with Cu catalyst (D, corresponding to Fig. 3A) and measured from the height profiles in AFM images. E,F) AFM images of ultralong SWNTs from Fe (E) and Cu (F) catalysts.

according to the statistic based on 118 tubes. For the Fe catalyst, the diameter of the SWNTs ranges from 1.0 to 1.2 nm according to the statistic based on 123 tubes. During AFM imaging, we also found that there is a larger amount of amorphous carbon in the Fe sample. This was also found in the case of ultralong SWNTs as shown in the AFM images in Figure 4E and F. Clearly there is more dirt in the Fe sample.

We found that the ultralong SWNTs obtained by the Cu catalyst are extremely suitable for building high-performance n- and p-type field-effect transistors (FETs).[34–37] The SWNT FETs show large I_{on}/I_{off} ratio (10^6 for back gate and 10^5 for top gate) and other excellent performance indicators, including high transconductance of up to 25 μS, a small subthreshold swing of 70 mV/dec, a room temperature on-state conductance of about $0.55G_0$ (with $G_0 = 4e^2/h$ being the quantum conductance limit of the SWNT), an electron mobility of 5100 $cm^2 V^{-1} s^{-1}$, and mean free length of up to 0.639 μm have been achieved. Figure 5 shows the performance of a CMOS inverter composed of a SWNT prepared with a Cu catalyst.[35] The Sc (source) and Pd (drain) electrodes were connected as shown in the inset of Fig. 5A. At forward bias, the increasing $V_{gs} = V_{ds}$ shifts the energy band of the SWNT remarkably downward, reducing the potential barrier for thermionic electron injection from the Sc contact to the Pd contact and leading to a dramatically enhanced electron current of about 13 mA at $V_{ds} = 5$ V.

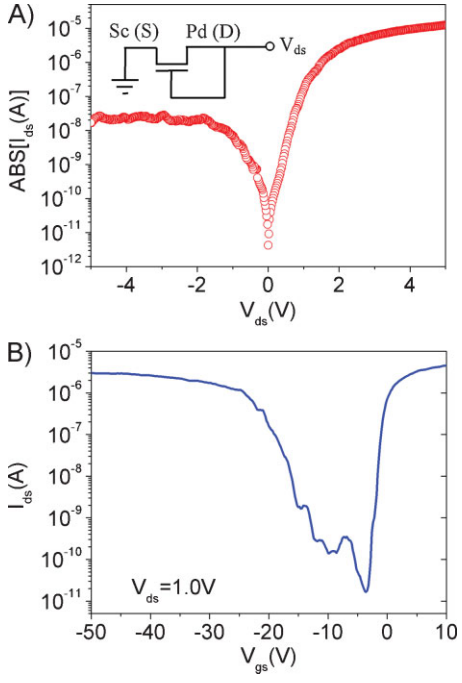


Figure 5. CMOS inverter based bipolar diode and ambipolar for a SWNT with diameter of ~1.5 nm and a channel length L of ~4 μm. A) Diode characteristic ($I_{ds} - V_{ds}$), showing the absolute magnitude of the drain current as a function of the drain bias when the gate and drain electrodes are connected together as shown in the inset. B) Transfer characteristic of the device, showing that the device is an ambipolar FET [35].

4. Pb: The Catalyst for Growing SWNTs without Metallic Contaminants

It was found that the Pb–C phase diagram is very similar to that of Cu–C. The solubility of carbon in Pb at the growth temperature of SWNTs (normally 850–950 °C) is also very similar to its solubility in Cu. This gives us a hint that Pb might also be able to act as a catalyst for the CVD growth of SWNTs. However, the melting point of Pb is as low as 327 °C and the vapor pressure of Pb should be very high at the growth temperature of SWNTs. Using Pb as the catalyst, no SWNTs were grown by the normal CVD process. Therefore, it is necessary to find a way to reduce the evaporation of Pb and fix the Pb nanoparticles during the nucleation and growth process of SWNTs. Reducing the gas flow, using fast-heating CVD[14] instead of the normal CVD process, or using polyvinylpyrrolidone (PVP) to cap the Pb nanoparticles can all remarkably relieve the evaporation of Pb and lead to the formation of SWNTs.[38] Figure 6A and B shows the SWNT arrays grown using Pb as the catalyst with PVP-capping of the catalyst and by the fast-heating method, respectively.

The most exciting thing is that the Pb catalyst can be eliminated thoroughly from the final product due to the volatility of Pb during the synthesis process.[38] We used in situ formed polymer films to peel off the SWNTs and all other species from the substrates. Then tens of such samples were nitrolized and the content of metal ions in the solution was analyzed with inductively coupled plasma (ICP). No metal ion species were detected. This shows that no metallic residues were present in the sample. However, the presence of Fe and Cu in SWNTs from Fe and Cu catalysts, respectively, were easily verified by a less sensitive technique such as energy-dispersive x-ray analysis (EDAX).[30] This kind of SWNT sample, with no metallic contaminants, is superior for the study of its intrinsic properties and applications in biological systems of SWNTs, and for building

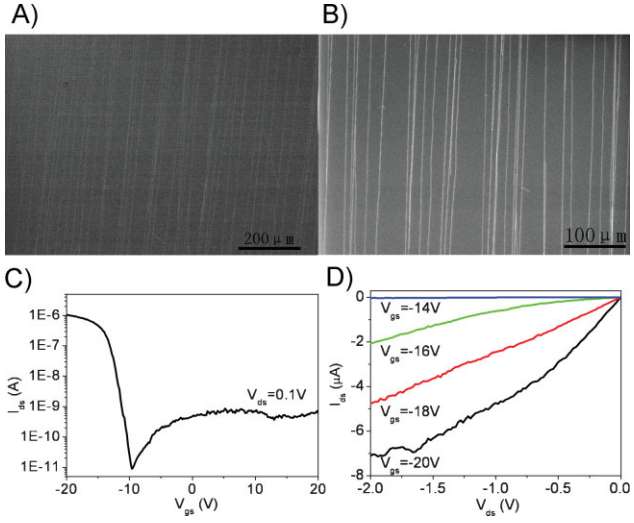


Figure 6. SEM images of SWNT arrays grown using Pb as the catalyst, with PVP capping of the catalyst (A) and by fast-heating method (B). The $I_{ds} - V_{gs}$ (C) and $I_{ds} - V_{ds}$ (D) curves of the FET device built from a single nanotube grown from Pb catalyst. Reproduced with permission from [38]. Copyright 2008, American Chemical Society.

high-performance nanodevices with SWNTs. The FET device made of a single SWNT obtained by a Pb catalyst showed high performance in electrical transport measurement (Fig. 6C and D).

5. Other Catalysts

In more recent studies, we found that many kinds of metals can be used to grow SWNT arrays on quartz substrates.[23] Co, Ni, Pt, Pd, Mn, Mo, Cr, Sn, Au, and even Mg and Al can be used as catalysts for growing SWNTs (Fig. 7). Although it is the first time for Co, Ni, Pt, Pd, Mn, Mo, and Au to be used for growing SWNTs on quartz substrates, these metals have already been used as catalysts for the preparation of SWNTs. It is even not very surprising for Cr and Sn to be able to act as catalysts though they have never been used for growing SWNTs before, because Cr is in the same group as Mo, and Sn is in the same group as Pb. However, Mg and Al are very different from those metals that have ever been used for catalyzing SWNTs' growth. This is the first report that IIA and IIIA metals can be used as catalysts for growing SWNTs.

The reason why the SWNTs were aligned on quartz substrates is still a dissension. Atomic steps or surface lattice of the substrates may be responsible for this. Here no regular atomic steps were observed on the surface of quartz substrates in our samples. And so many kinds of catalysts could all produce aligned SWNTs on quartz. This indicates that most probably the interaction between the surface lattice of the substrate and the carbon shell precipitated on the outer surface of the catalysts takes the key role in SWNTs' alignment.[23]

Very recently, there are reports that oxides including SiO_2[39,40] and ZrO_2[41] can be used to catalyze the CVD growth of SWNTs. Even diamond is able to nucleate the growth of SWNTs.[42] These results enrich the diversity of catalysts for CVD growth of SWNTs. It may also call our attention to rethinking the growth mechanism of SWNTs.

6. Conclusions

Catalysts are a very important issue for the controlled preparation of SWNTs on substrates. We have developed a series of methods to control the size, the distribution, and the deposition and positioning of the catalyst nanoparticles on substrates. High-quality random networks and horizontally aligned arrays of SWNTs were obtained with these catalysts. Besides studies on the widely used Fe-based catalysts, we also found some new catalysts. Among these new catalysts, Cu and Pb are very unique. Cu is a superior catalyst for growing SWNT arrays on both quartz and silicon substrates. Ultralong SWNTs on SiO_x/Si substrates prepared from Cu are extremely suitable for building high-performance FETs. On quartz substrates, SWNTs of very high density and pure semiconducting SWNTs were obtained. Pb is of importance because it can produce pure SWNTs with no metallic contaminants. This is a great advantage for the application of SWNTs.

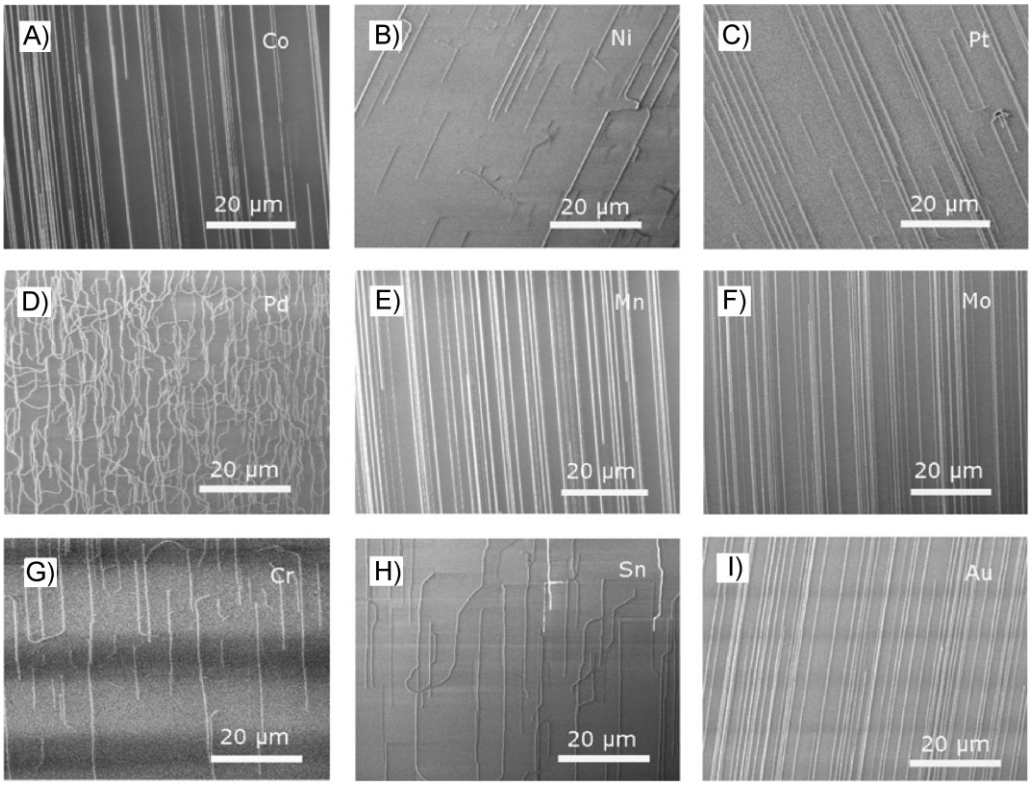


Figure 7. SEM images of horizontally aligned SWNTs growth by A) Co, B) Ni, C) Pt, D) Pd, E) Mn, F) Mo, G) Cr, H) Sn, and I) Au. The alignment direction is the *X* direction on ST-cut quartz. Reproduced with permission from [23]. Copyright 2008, American Chemical Society.

The control of the orientation, position, dimension, structure, and property of SWNTs in the preparation process is very important for the further application of SWNTs especially in the area of nanoelectronics. The biggest challenge in SWNT fabrication is the (*n*,*m*)-specified preparation of SWNTs. The selection of the right catalyst is shown to be a possible route for this goal.[43] The comprehensive study on the relation between the size, composition, and structure of the catalyst nanoparticles and the structures of the produced SWNTs will conduce the in-depth understanding of the growth mechanism of SWNTs. Then the precise control over the structure and property of SWNTs can be anticipated. In addition, the selection of a proper catalyst is also helpful for controlling the position and orientation of SWNTs on substrates. The realization of accurate control over the position, orientation, and structure (property) of SWNTs will be the prerequisite to the commercial application of SWNTs in reliable and durable nanoelectronics.

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