

# Chemical Vapor Deposition Growth of Single-Walled Carbon Nanotubes at 600 °C and a Simple Growth Model

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Received: October 10, 2003; In Final Form: December 3, 2003

A comparison of different catalysts (Ni, Co, Fe/Mo) has been performed in order to minimize the growth temperature for single-walled carbon nanotubes (SWCNTs). Dense SWCNT networks have been synthesized by thermal chemical vapor deposition (CVD) at temperatures as low as 600 °C using Ni catalyst layers of approximately 0.2 nm thickness. The dependence of the SWCNT growth on the most important parameters will be discussed exemplarily on the Ni catalyst system. On the basis of experimental observations, a phenomenological growth model for CVD synthesis of SWCNTs is proposed which is based on the interactions between the catalyst and its support. Further, it is suggested that only surface diffusion of hydrocarbons on the catalyst support or along the CNTs can explain the fast growth rates of SWCNTs during CVD synthesis.

## Introduction

The direct CVD synthesis of SWCNTs on appropriate substrates seems to be one of the most promising methods for their integration into future devices.<sup>1,2</sup> To achieve a high degree of compatibility with standard semiconductor processes it is crucial that the growth temperatures are as low as possible while maintaining a high yield and good quality. Further, the principal growth mechanisms have to be well understood.

In the past few years there have been already a number of publications on the CVD synthesis of SWCNTs with respect to high yield and low growth temperatures. Kong et al. extensively studied the growth of high-quality SWCNTs.<sup>3</sup> Low growth temperatures were reported by Mo et al.,<sup>4</sup> who synthesized a mixture of SWCNTs and MWCNTs at 600 °C using a mechanically mixed Al<sub>2</sub>O<sub>3</sub>/Ni catalyst. However, an activation anneal at 900 °C was carried out before starting the growth using an acetylene/hydrogen mixture. Furthermore, SWCNT growth using solution-based Fe/Mo mixtures supported on alumina particles has been observed at temperatures as low as 680 °C.<sup>5,6</sup>

The growth of SWCNTs on multilayered catalysts had been studied by a number of groups. First Delzeit et al. found enhanced SWCNT growth from a thin Fe/Mo bilayer on top of a 2–10 nm Al underlayer at 900 °C with methane as the carbon feedstock.<sup>7</sup> Recently, growth of SWCNTs at 800 °C has been reported using an Al/Ni bilayer and a hydrogen/methane gas mixture.<sup>8</sup> Growth on Al/Co bilayers at 750 °C with methane and at 700 °C with acetylene has been previously reported by our group.<sup>2,9</sup> Cui et al. studied CNT growth at temperatures from 500 °C to 1100 °C using a 0.2 nm Mo/1 nm Fe bilayer on 10 nm Al and acetylene.<sup>10</sup> This group observed around 900 °C both SWCNTs and double-walled carbon nanotubes (DWCNTs), but at lower temperatures they reported only the growth of MWCNTs.

In this paper, we present results on the CVD synthesis of SWCNTs using Ni, Co, Fe/Mo, and Co/Fe as the catalyst. We

also show that the use of Ni enables SWCNT synthesis at temperatures as low as 600 °C. We derived a simple phenomenological model for the CVD growth of SWCNTs based on our observations and compare it with other models.

## Experimental Section

The metal layers, both catalyst and support, used in the experiments were deposited using a high-precision ion-beam coater. This system allows the reproducible deposition of layers as thin as 0.2 nm. All multilayers systems were deposited on thermal Si-oxide. The samples were characterized after growth by scanning electron microscopy (SEM) using a Leo 1560 microscope. The successful growth of SWCNTs was demonstrated by transmission electron microscopy measurements (Phillips CM2010) together with Raman spectroscopy (Jobin Yvon, Labram, 633 nm He/Ne laser) and electrical transport measurements. The latter ones were conducted on SWCNTs grown between contact pads and using the Si-substrate as the back-gate.<sup>2</sup>

The growth experiments were performed by loading the samples into the hot quartz-tube furnace before evacuating to below 10<sup>-3</sup> Torr and beginning hydrogen pretreatment of the catalyst at 2.5 Torr. Depending on the production regime, growth was initiated by partially filling the oven with methane, a methane/hydrogen mixture, or an acetylene/hydrogen mixture.

## Results

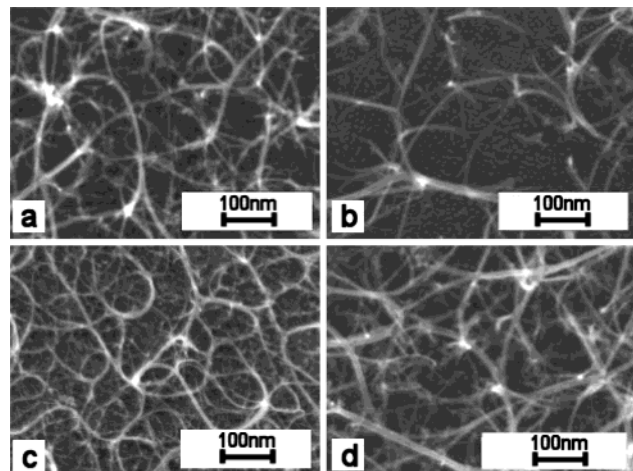
A number of systematic experiments were conducted in order to achieve CVD growth at low temperatures. The different catalysts together with the corresponding support layers and growth parameters (carbon feedstock, pressure during growth, pretreatment time, and growth temperatures) that yield SWCNTs are summarized in Table 1. An impression of the high yield of SWCNTs that have been grown with Ni, Co, or Fe/Mo catalysts can be obtained from the SEM images in Figure 1. Note that the up to 20 nm wide structures consist of dense SWCNT bundles which unravel and form branches at various points.

The most important parameters for SWCNT growth have turned out to be the catalyst material, catalyst layer thickness,

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**TABLE 1: Parameters for the CVD Growth of SWCNTs (The multilayers were sputtered on thermal SiO<sub>2</sub>)**

catalyst	catalyst thickness [nm]	catalyst support	carbon feedstock	pressure during growth [Torr]	H <sub>2</sub> pretreatment time	temperature range
Ni	0.2–0.3	Al	methane	375 CH <sub>4</sub>	5–60 min	600–800 °C
Ni	0.2	SiO <sub>2</sub>	methane	375 CH <sub>4</sub>	< 5 min	600 °C
Co	0.2–0.3	Al	methane	375 CH <sub>4</sub>	5 min	700–850 °C
Co/Fe	<0.2/<0.2	Al	methane	375 CH <sub>4</sub>	5 min	~750 °C
Co	0.2–0.3	Al	acetylene	2.5 H <sub>2</sub> + 5 C <sub>2</sub> H <sub>2</sub>	5 min	700–750 °C
Fe/Mo	<0.2/0.2	Al	methane	100 H <sub>2</sub> + 200 CH <sub>4</sub>	5 min	900 °C



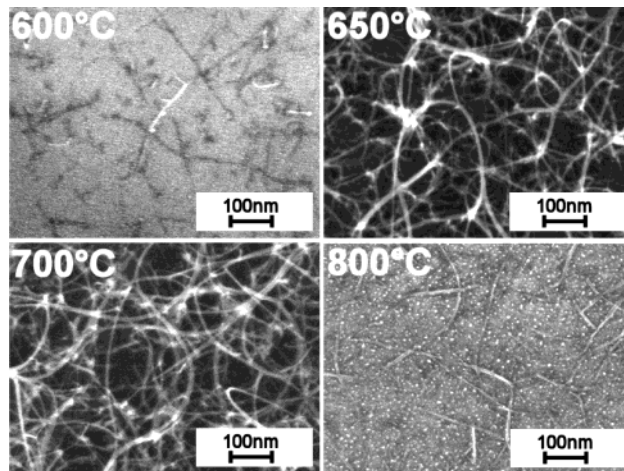
**Figure 1.** SEM micrographs of SWCNTs synthesized with different catalyst materials. The catalyst was deposited on thermal SiO<sub>2</sub> with a 5 nm Al support layer (compare to Table 1). (a) 0.2 nm Ni, 700 °C, methane; (b) 0.2 nm Co, 750 °C, methane; (c) 0.2 nm Co, 700 °C, acetylene; (d) <0.2 nm Mo/0.2 nm Fe, 900 °C, methane.

temperature, pretreatment time, gas pressure, and the catalyst support. The growth of SWCNTs using Ni as the catalyst will be exemplarily discussed in detail since it enables SWCNT synthesis at the lowest temperatures and some of the other catalyst systems have been already discussed elsewhere.<sup>2,7,9</sup>

It has been shown recently that the use of Al as catalyst support plays an important role for successful SWCNT growth.<sup>2</sup> We now observed that slight variations of the catalyst thickness on the scale of 0.1 nm will greatly affect the extent of the growth. With increasing catalyst layer thickness, the density of catalyst particles also increases, but in contrast to this the yield of SWCNTs decreases. This may be explained by the fact that increasing fraction of the catalyst particles becomes too large to promote SWCNT growth or, alternatively, that the high density of particles hinders the growth.

Examples of the temperature dependence of the growth of SWCNTs for the Al/Ni system are shown in Figure 2. In this experiment all parameters besides temperature were kept constant. At 600 °C the growth is very sparse since an insufficient number of active catalyst particles forms during the 5 min pretreatment in hydrogen. Between 650 °C and 700 °C, good growth is observed. At 800 °C the yield of CNTs is clearly reduced and many large catalyst particles are visible. These particles can easily form at higher temperatures by Oswald ripening but are unable to support SWCNT growth, because they are already too big.

The duration of the hydrogen pretreatment was found to be very important for successful growth. Figure 3 shows the effect of the H<sub>2</sub> pretreatment time on the SWCNT yield at 650 °C. A pretreatment of 5 min is not sufficient and a pretreatment of 60 min is too long to enable good SWCNT growth, whereas after 10 min of pretreatment a sufficient growth of SWCNTs was observed.

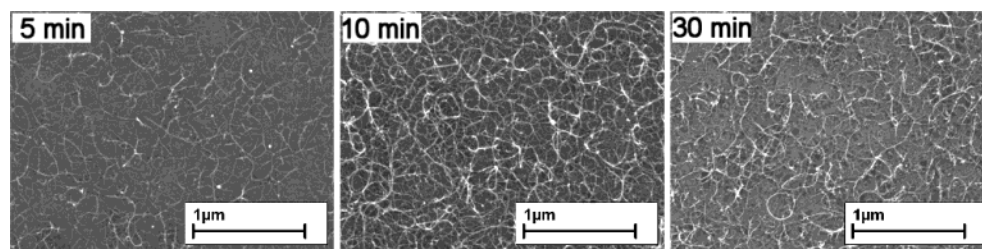


**Figure 2.** Temperature dependence of the SWCNT growth on samples consisting of a 100 nm thermal oxide substrate with 6 nm Al and 0.3 nm Ni catalyst. CNT growth was made after 5 min H<sub>2</sub> pretreatment for 10 min using a methane pressure of 375 Torr.

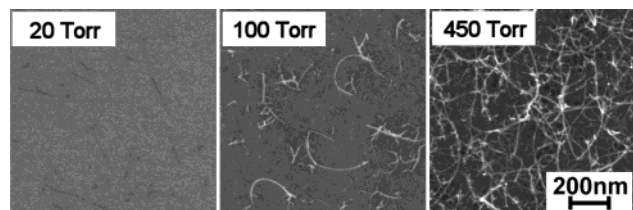
Another important influence on the SWCNT growth is the gas pressure, which is illustrated in Figure 4. Only a sufficiently high methane pressure supports good growth. Nevertheless, some isolated SWCNTs (Figure 4a—dark lines) can be observed, even at pressures as low as 20 Torr. At higher temperatures, the partial pressure of the carbon carrier gas is limited by its pyrolytic activity.

Figure 5 illustrates the influence of another important parameter, namely the catalyst support. In Figures 5a and 5b, the Ni catalyst has been deposited on plain SiO<sub>2</sub>, whereas in Figures 5c and 5d a 3 nm Al layer acts as the catalyst support. The samples in Figure 5a and 5c have been pretreated at 600 °C with hydrogen for 10 min, whereas the samples in Figure 5b and 5d were each pretreated for 60 min before growth at the same temperature. The difference between growth on plain SiO<sub>2</sub> and on the Al layer is obvious. Satisfying growth on SiO<sub>2</sub> at a temperature of 600 °C (Figure 5a) requires much smaller pretreatment times than growth at the same temperature on an Al support (Figure 5d). A 10 min pretreatment (Figure 5c) is not sufficient for the samples with an Al support to promote SWCNT growth. An explanation for this difference is that the Ni atoms probably diffuse faster on SiO<sub>2</sub> than on the Al support, and consequently a shorter pretreatment time is required for SWCNT growth on SiO<sub>2</sub>. Large catalyst particles form on SiO<sub>2</sub> at longer pretreatment times (Figure 5b), inhibiting SWCNT growth.

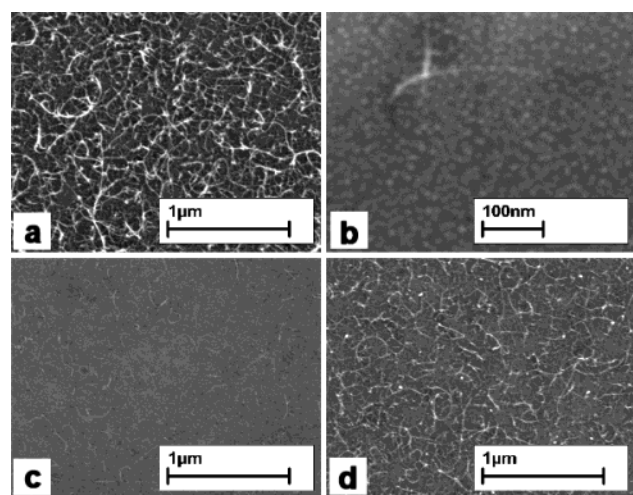
To our knowledge the exclusive growth of SWCNT at such low temperatures has not been reported before. Figure 6 shows the radial breathing modes in the Raman spectra of SWCNTs grown at 600 °C. The four different overlapping spectra were obtained at four different positions on the same sample. They show all a very similar response. A detailed analysis of the diameter distribution would require more than one excitation energy and still needs to be done. The diameters of the excited



**Figure 3.** Effect of the  $\text{H}_2$  pretreatment time on SWCNT growth at  $650^\circ\text{C}$  (100 nm thermal oxide/3 nm Al/0.2 nm Ni, 10 min growth, 375 Torr  $\text{CH}_4$ ). Short and long pretreatment times lead to reduced CNT density.



**Figure 4.** The dependence of CNT growth on the methane pressure (100 nm thermal oxide/6 nm Al/0.2 nm Ni,  $650^\circ\text{C}$ , 5 min  $\text{H}_2$  pretreatment, 10 min growth).

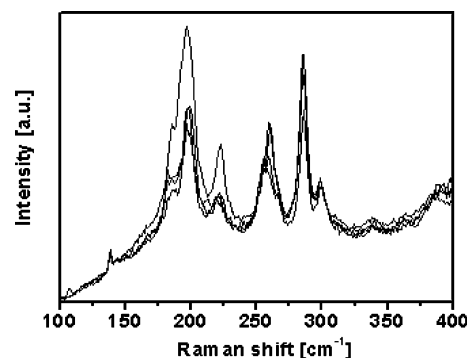


**Figure 5.** The effect of the duration of hydrogen pretreatment on SWCNT growth at  $600^\circ\text{C}$  using 0.2 nm Ni catalyst on either plain  $\text{SiO}_2$  ((a) and (b)) or 3 nm Al on  $\text{SiO}_2$  ((c) and (d)). Samples (a) and (c) had been each pretreated for 10 min, (b) and (d) each for 60 min (growth time: 10 min;  $\text{CH}_4$  pressure: 375 Torr).

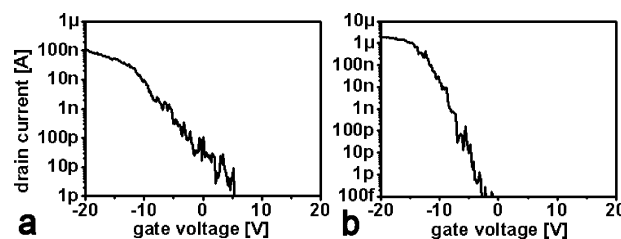
nanotubes were calculated from the radial breathing mode frequency to be approximately between 0.78 and 1.3 nm.<sup>11</sup>

Electrical transport measurements revealed the existence of semiconducting SWCNTs. The semiconducting behavior could be proven by field effect measurements. Only semiconducting SWCNTs and not MWCNTs exhibit this behavior at room temperature. Figures 7a and 7b show the drain-current vs gate voltage curves of two SWCNTs grown at  $600^\circ\text{C}$  and  $700^\circ\text{C}$ , respectively. The SWCNTs have been grown between Ti/Mo or Ta/Co electrodes for these kinds of measurements. The contacts of both samples have been improved after the growth by a subsequent electroless Ni deposition.<sup>2</sup> A detailed discussion of the electronic properties is however not the scope of this work.

At temperatures lower than  $600^\circ\text{C}$ , the growth rate is drastically reduced. Figure 8 shows an experiment at  $575^\circ\text{C}$  on plain  $\text{SiO}_2$ . The density of CNTs is low and also the length does not exceed several hundreds of nanometers. At such low temperatures, surface diffusion of carbon species may be the growth limiting factor. The temperature has to be high enough



**Figure 6.** Radial breathing mode response in the Raman spectra of SWCNTs grown at  $600^\circ\text{C}$  using a 0.2 nm Ni catalyst layer on quartz and methane as the carbon source. The four spectra, taken at different locations on the substrate, show all a very similar response indicating a homogeneous, reproducible growth. The diameters of the excited nanotubes were calculated from the radial breathing mode frequency to be approximately between 0.78 and 1.3 nm.



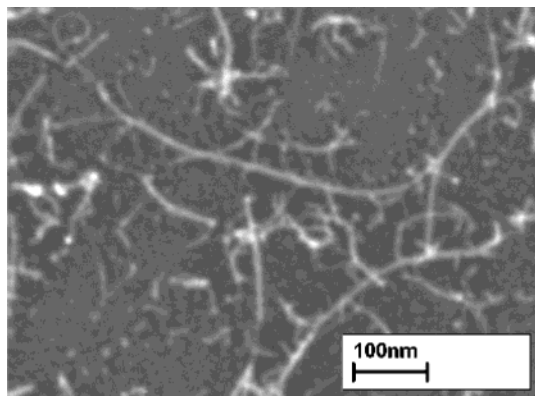
**Figure 7.** Field effect measurements using the Si substrate as a back-gate that prove the growth of (semiconducting) SWCNTs. Measurements were performed at room temperature, in air, and with a bias of 100 mV. (a) Drain current vs gate voltage of an in-situ contacted SWCNT synthesized at  $600^\circ\text{C}$ . (b) Drain current vs gate voltage of a SWCNT synthesized at  $700^\circ\text{C}$ . Both samples were measured after contact improvement by electroless Ni deposition (multilayer: 200 nm thermal  $\text{SiO}_2$ , 20 nm Ta, 50 nm Co, 5 nm Al, 0.2 nm Ni catalyst).

to allow sufficient diffusion of both the catalyst atoms and the carbon species.  $600^\circ\text{C}$  seems to be the minimum possible temperature which still supports the thermal CVD growth of well-graphitized CNTs. At lower temperatures, only carbon nanofibers or bamboo-shaped CNTs can be synthesized by thermal CVD, as observed by ourselves and other groups.<sup>12</sup>

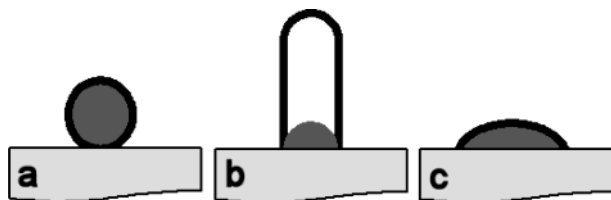
## Discussion

The difference of the growth behaviors of Fe, Co, and Ni may be related to their ability to form catalyst particles with the right size and shape. Interestingly, the order of the lowest growth temperatures is in agreement with the order of the bulk melting points of the three transition metals (Ni,  $1450^\circ\text{C}$ ; Co,  $1490^\circ\text{C}$ ; Fe,  $1540^\circ\text{C}$ ). This might explain why Ni exhibits the lowest growth temperature. If the atoms can diffuse more easily on the catalyst support they can coalesce into particles more rapidly (Figure 9b). On the other hand, if the atoms diffuse too quickly, the particles will become too large to initiate





**Figure 8.** Only sparse growth of SWCNTs can be observed at a temperature of 575 °C (0.2 nm Ni catalyst on 100 nm SiO<sub>2</sub>, 5 min H<sub>2</sub> pretreatment, 10 min growth, 375 Torr CH<sub>4</sub>).

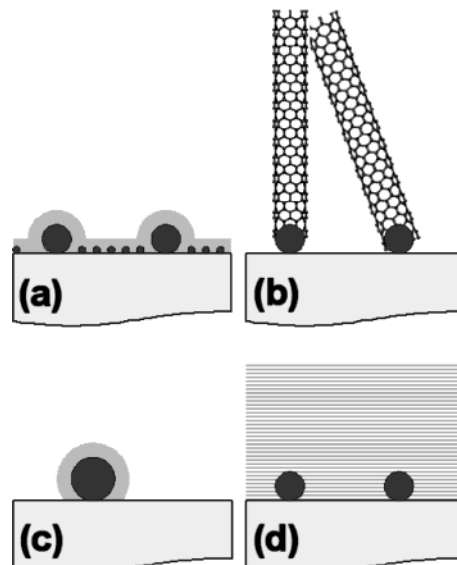


**Figure 9.** Schematic that shows the effect of the interaction between the catalyst support and the catalyst on the SWCNT growth. A weak interaction (a) inhibits SWCNT growth since the catalyst particles become too large, a moderate interaction (b) gives particles with the right size and shape for SWCNT growth, whereas a strong interaction (c) prevents formation of suitable particles.

SWCNT growth (Figure 9a). The shape of the catalyst particles is largely affected by their wetting behavior on a specific substrate. It has been reported that hydrogen leads to much better wetting.<sup>13</sup> Thus, the pretreatment in H<sub>2</sub> might not only reduce the metal oxide, but also improve the wetting of the catalyst particle. A strong interaction between catalyst atoms and the catalyst support or even a slight inter-diffusion will hinder the formation of appropriately shaped catalyst particles (Figure 9c). The concept of the importance of the catalyst support on SWCNT growth becomes more obvious if one regards the limited choice of substrates (e.g., SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, MgO) on which SWCNTs and also high quality MWCNTs (no bamboo-shaped CNTs or carbon nanofibers) can be grown.

The surface diffusion rate of a specific atom also depends on the roughness of the catalyst support and the temperature.<sup>14</sup> Although, a metallic Al layer has been deposited below the catalyst, this layer is at least partially oxidized to alumina during the growth process.<sup>2</sup> This means that the catalyst particles are in contact with alumina rather than with metallic Al. The surface roughness of the Al layer is higher than that of thermal SiO<sub>2</sub>, since ion-beam deposition or e-beam evaporation of Al on SiO<sub>2</sub> usually produces an additional surface roughness due to island growth. This surface roughness hinders the surface diffusion of the catalyst and, thus, the coalescence into larger particles. In addition, the surface diffusion parameters of the catalyst atoms on SiO<sub>2</sub> will be different from those on alumina. This is one possible explanation for the growth of SWCNTs over a wider temperature range on a thin Al support layer compared to growth on plain SiO<sub>2</sub>.

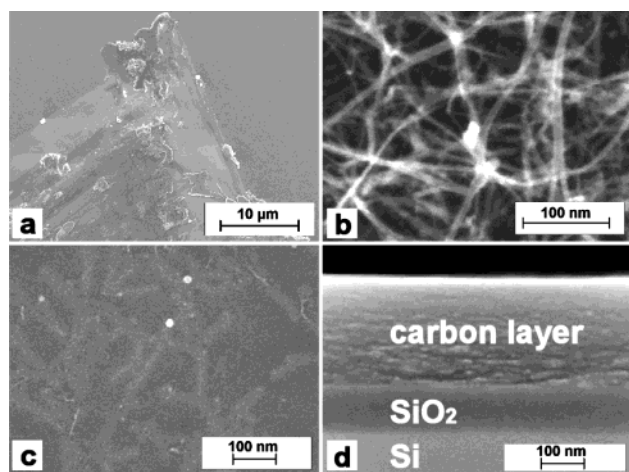
It has been suggested that SWCNT growth is initiated once a carbon monolayer covering a catalyst particle becomes unstable due to incorporation of additional carbon atoms or thermal vibrations.<sup>13,15,16</sup> However, when considering the growth of SWCNTs, two components have largely been neglected. First,



**Figure 10.** Critical scenarios during a SWCNT CVD process: (a) surface poisoned by catalyst clusters (interaction between catalyst and support too strong, temperature too low, H<sub>2</sub> pretreatment time too short); (b) good SWCNT growth; (c) catalyst particles too large (interaction between catalyst and support too weak, temperature too high, H<sub>2</sub> pretreatment time too long); (d) an amorphous carbon or graphite layer forms at the high temperature or high-pressure limit of the process.

the interaction of the catalyst with the catalyst support affects both the size and the shape of the catalyst particles (Figure 9). Second, a large portion of the catalyst particle is covered with a monolayer of carbon or the growing carbon nanotube, hindering the catalytic decomposition of the carbon feedstock at the surface of the catalyst particle. In addition, the impingement rate of carbon species at the nanometer-sized particles directly from the gas phase might be too low to explain the fast growth of SWCNTs. One or both of the following two mechanisms could deliver the flow of carbon required for the observed SWCNT growth rate: (1) surface diffusion of adsorbed carbon species along the outer walls of the SWCNTs,<sup>14</sup> and (2) surface diffusion on the oxide surface (e.g., SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, MgO) supporting the catalyst particles.

Due to concentration gradients along these surfaces, the carbon species will diffuse to the roots of the SWCNTs. Growth then proceeds by incorporation of carbon atoms at the dangling bonds or by carbon pentagon-to-hexagon transformations around the catalyst particle. The final decomposition of the carbon species to pure carbon may occur at the point where the carbon atom is incorporated at a dangling bond. It is very likely that a certain amount of hydrocarbon is adsorbed on the oxide surfaces. To support this assumption, we consider the pyrolytic activity of gases such as acetylene and methane. At sufficiently high temperatures and partial pressures, thick amorphous carbon layers form on the substrates (Figure 11d). Experiments have shown that the pyrolytic decomposition on the substrate starts at temperatures well below those at which autopyrolysis in the gas phase occurs. Autopyrolysis results in the formation of amorphous carbon flakes. This indicates that even at lower temperatures a certain amount of hydrocarbon will always adsorb on the oxide substrate. Further, it has also been reported that multiwalled carbon nanotube-like structures can be synthesized in the pores of AAO templates without the help of a catalyst.<sup>17</sup> The adsorbed hydrocarbons have to be sufficiently mobile to diffuse to the catalyst particles where they can be incorporated into the SWCNTs. The supply of hydrocarbons to the growing SWCNTs can be limited by the growth temperatures



**Figure 11.** SEM images of (a) amorphous carbon on a sample with insufficient annealing (carbon layer scratched with tweezers; 100 nm thermal oxide, 6 nm Al, 0.2 nm Ni; 600 °C; 375 Torr CH<sub>4</sub>); (b) abundant SWCNT growth and bundle formation (5 nm Al, ~0.2 nm Ni, 700 °C); (c) poor growth due to too large catalyst particles (5 nm Al, ~0.4 nm Ni, 700 °C, 5 min pretreatment, 10 min growth, 375 Torr CH<sub>4</sub>); (d) cross-section showing a pyrolytic carbon layer on SiO<sub>2</sub> (950 °C, 375 Torr CH<sub>4</sub>).

and the free catalyst support surface around each particle. In the latter case, insufficient hydrocarbon species diffuse along the surface to the catalyst particles, i.e., the rate is too slow.

Figures 10 and 11 schematically and experimentally illustrate four principal situations that may occur during a CVD process and support the proposed growth model based on catalyst substrate interactions and on surface diffusion:

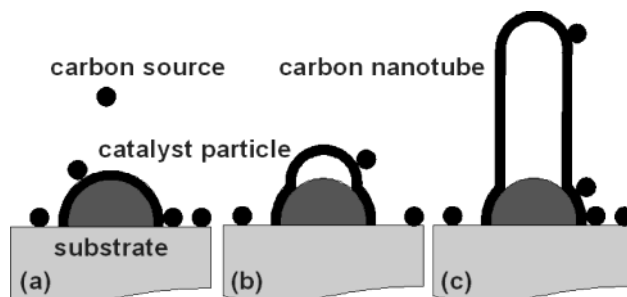
(a) The catalyst particles interact too strongly with the support, the H<sub>2</sub> pretreatment time is not sufficient, or the temperature is too low (Figure 10a). At temperatures too low for SWCNT synthesis, a thin amorphous carbon coat grows on the substrate surface which was observed by scratching the sample with tweezers (Figure 11a). There are two possible reasons for the formation of this layer: First, small catalyst clusters and isolated catalyst atoms that did not coalesce to particles poison the catalyst support surface. Second, insufficient carbon is delivered to the growth sites by the low surface diffusion of the carbon species.

(b) Figure 10b and Figure 11b illustrate the ideal case with good SWCNT growth where all parameters are within the specific process window.

(c) The catalyst interacts too weakly with the support, the H<sub>2</sub> pretreatment time is too long, the catalyst layer is too thick, or the temperature is too high. Here the catalyst particles will become too large (>3 nm) and SWCNTs cannot grow (Figure 10c and Figure 11c).

(d) The growth temperature is too high for the specific partial pressure of the carbon feedstock. Here pyrolytic processes on the support will dominate and hydrocarbons adsorb on the substrate faster than they can be incorporated in SWCNTs. As a result, either a thick amorphous carbon layer or a graphite layer will form, burying the catalyst particles (Figure 10d, Figure 11d).

The growth process may be initiated via relaxation of the strain built up in the carbon cap or shell around the spherical surface of a catalyst particle (Figure 12a). The strain is developed by the formation of fullerene like pentagon–hexagon structure that later forms the tip of the SWCNT because it is highly unlikely that the cap will perfectly fit onto the catalyst particle. Strain may also be caused by the interaction of the



**Figure 12.** Relaxation mechanism of a strained carbon cap (a) that initiates SWCNT growth (b). The growth continues by incorporation of carbon atoms at the catalyst particle combined with an extrusive force resulting from a slightly strained CNT shell.

increasing cap surface and the adhesion forces of the catalyst particle on the support (wetting). If the cap slips off the catalyst particle, the strain will be partially released (Figure 12b). The resulting extrusive force persists as long as new carbon atoms are incorporated at the dangling bonds (Figure 12c). Vinciguerra et al. proposed a similar extrusive-diffusive model.<sup>18</sup> They also proposed that the carbon species are delivered by diffusion along the catalyst support to the catalyst particle. In that model the growth had been explained by an extrusive force opposing a friction force. They suggested that the extrusion force results from a free energy release, whereas the friction force results from interaction of the CNTs with the surrounding gas. In contrast we rather suggest that the growth is inhibited by van der Waals forces between different CNTs (bundle formation) or the substrate surface.

One consequence from this model is that the catalytic activity of the catalyst particle is only important for the nucleation of the nanotube (supersaturation with carbon) but not for the subsequent growth.<sup>14</sup> This might also explain why SWCNTs could even be synthesized without catalyst particles at higher temperatures.<sup>19</sup> Here the nucleation of the SWCNTs was probably initiated by a nanoscopic surface roughness or by thermal vibrations alone (growth temperature 1500 °C). Further the model presented here describes an alternative mechanism to the vapor–liquid–solid (VLS) process, which is based on the solution of a gaseous carbon phase in a liquid catalyst particle.<sup>13,20</sup> Bulk diffusion in the catalyst particle, which is a condition for the VLS mechanism, requires higher activation energies than surface diffusion.<sup>21</sup> Thus, we propose that more rapid diffusion on the surface causes the fast growth rates of the SWCNTs during CVD synthesis. The growth of individual MWCNTs from nanoholes is also supported by this diffusion model.<sup>22</sup> Since the holes are filled completely by the nanotubes, the carbon supply must be provided via diffusion on the surface of the substrate or the tube. Bulk diffusion may become more important at higher temperatures.<sup>23</sup> i.e., a growth model based on the supersaturation of the catalyst particles with carbon may be relevant during high-temperature processes (arc discharge, laser ablation).

The surface diffusion model presented above can also be applied to explain DWCNT and MWCNT growth assuming that larger catalyst particles need caps consisting of more graphene shells in order to become unstable and initiate CNT growth. The simultaneous growth of different diameter MWCNTs from confined catalyst particles under the very same conditions has been observed. Thus, in contrast to the widespread assumption,<sup>24</sup> that SWCNTs need a higher growth temperature than MWCNTs, the results presented above show that the CVD synthesis of SWCNTs and MWCNTs using hydrocarbons takes place within the same temperature range (600–900 °C).

## Conclusions

In conclusion, SWCNTs could be synthesized by thermal CVD at temperatures as low as 600 °C. By comparing Ni, Co, and Fe/Mo as the catalyst material on an Al support layer it was found that Ni allows the synthesis of SWCNTs in the lowest temperature range. The importance of a number of parameters in the Al/Ni system has been investigated. On the basis of a number of experimental observations we propose a growth model in which surface diffusion of carbon species along the catalyst support or along the walls of the SWCNTs is of fundamental importance. Further, it has been shown that the interaction between catalyst and catalyst support greatly affects the growth behavior. Finally, an extrusion mechanism based on a strained carbon shell or a strained nanotube has been suggested to enhance or even initiate the growth of SWCNTs. This may help to assess the potential of thermal CVD for the future integration of SWCNTs into various devices.

**Acknowledgment.** This work has been funded by the German Ministry of Science and Technology (BMBF) under Contract No. 13N8402.

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