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Carbon



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ABSTRACT

The conductivity enhancement of single-walled carbon nanotube (SWCNT) films was achieved by increasing the bundle length in an aerosol CVD synthesis method with the help of two carbon sources. Carbon monoxide provides carbon at temperatures below 900 °C, while ethylene takes over at higher temperatures. The significant decrease in the sheet resistance at the 90% transmittance was observed from 3500 to 7500 Ω /sq. for pure CO system via 1909 and 1709 Ω /sq. for CO-H₂ system to 291 and 358 Ω /sq. in the presence of C₂H₄ at 900 and 1100 °C, respectively. Doping the film with a gold chloride solution in acetonitrile allowed us to create the transparent conductive films with the sheet resistance as low as 73 Ω /sq. at a transmittance of 90%.

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1. Introduction

Single-walled carbon nanotubes (SWCNTs) are a unique material with diverse exceptional properties, which could be utilized in many fields of science and technology. SWCNTs are the strongest known material with extraordinary high Young's modulus of elasticity and tensile strength [1,2]. SWCNTs possess very high porosity and high specific surface area. Due to very high current density, which tubes can with-stand without destruction, up to 10⁹ A/cm², SWCNTs are believed to be an ideal material for copper and aluminium replacement in integrated circuits. The most fascinating property, electronic structure of SWCNTs, provides many interesting applications in photonics and electronics. Owing to high conductivity and transparency, SWCNT films are a strong candidate for the replacement of commonly used transparent electrodes, such as indium-tin oxide (ITO), which

has several drawbacks, including high refraction and haze, limited flexibility, restricted chemical robustness and depleted raw material supply. SWCNT networks have been demonstrated to show potential advantages in performance and fabrication cost reduction in comparison with ITO as well as most of organic materials that have been extensively studied as low-cost alternatives [3]. Furthermore, high flexibility of the SWCNTs opens avenues beyond the ITO, i.e. creation of completely new components, needed in the flexible and transparent electronics.

The techniques currently utilized for the carbon nanotube film preparation are associated with certain difficulties. Substrate chemical vapor deposition (CVD) method is industrially limited by the choice of the substrates suitable for high temperatures required for the SWCNT growth. Solution-based SWCNT thin film preparation is a multi-step time and resource consuming method, including potentially detrimental liquid

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purification and dispersion steps, which eventually produce the films of defected SWCNTs due to ultrasound treatment. Recently, the aerosol CVD synthesis was integrated with SWCNT dry deposition at room temperature to solve the mentioned problems [4,5]. The SWCNTs produced by ferrocene decomposition in a CO atmosphere are first deposited by filtering the outlet flow on low adhesive force filters and then transferred from the filter to practically any substrate including heat sensitive, flexible and transparent substrate materials. Importantly, the SWCNTs synthesized by the aerosol method [6–8] meet all the requirements for low-cost, flexible and transparent electronics, which could be used in many high technology applications like touch sensors and displays, flexible and transparent electrodes in photovoltaic devices, optoelectronic devices, OLEDs, etc.

However, even the state-of-the-art SWCNT film conductivity [5] should be still improved to meet industrial requirements for certain applications to replace ITO. The optoelectronic properties of the produced SWCNT films depends on many parameters: quality, length, diameter, metallicity and chirality of SWCNTs comprising the film; length, morphology and diameter of bundles; orientation of the SWCNTs and doping [4,9–11]. The synthesis of SWCNTs with a certain chirality or metallicity is a promising, but still challenging way to improve the conductivity. The length of individual SWCNTs and therefore the bundle length are primary and the most important parameters, which define the film conductivity of randomly oriented SWCNT films.

In this paper, we report the improvement of the film conductivity by tuning the bundle length of SWCNTs. Since in the aerosol CVD synthesis reactor the growth of SWCNTs occurs in a certain region (growth zone) [12,13], the length of the produced SWCNTs depends on the residence time and growth rate. Taking into account that the latter is thought to be limited by the carbon diffusion in catalyst particles [13,14], the easiest way to tune the SWCNT length would be to increase the temperature in the reactor. However, as has been recently revealed the growth of SWCNTs in pure CO system occurs below about 945 °C, since at ambient pressure and at higher temperatures the Boudouard reaction, $2CO \iff C + CO_2$, is thermodynamically forbidden [13,15]. Therefore, to efficiently utilize the time available in the growth zone we added ethylene (C_2H_4) , which might take a role of the carbon source at the temperatures above 900 °C. However, in order to control the non-catalytic C₂H₄ decomposition we need to introduce a certain amount of hydrogen. As a result, we were able to tune the length and the yield of the SWCNTs. Finally, the SWCNT film doped by gold chloride (AuCl₃) exhibited the sheet resistance as low as 73 Ω /sq. at the transmittance of 90% at 550 nm.

2. Experimental details

Experimental investigations were carried out in a lab scale aerosol (floating catalyst) CVD reactor described elsewhere [8,16,17]. The total flow rate through the ferrocene cartridge introduced via water cooled injector was maintained at 350 cm³/min and regulated by varying the flow rates of CO (AGA, 2.0 grade) and H₂ (AGA, 5.0 grade). Additional outside CO flow was introduced at 150 cm³/min. All gases were

cleaned from oxygen containing species in prior to their utilization using OxySorb filter (Spectron, Germany).

High-resolution TEM images were obtained using a double Cs corrected microscope JEOL JEM-2200FS. To minimize the destructive influence of electron irradiation all samples were analyzed at the acceleration voltage of 80 kV with minimal possible electron illumination time. Raman spectroscopy measurements were carried out using a Horiba Jobin Yvon LabRAM 300 spectrometer with a 633 nm laser.

Usually for optoelectrical characterization of the SWCNT films, sheet resistance (R_s) and optical transmittance (T) at 550 nm are used. In order to have possibility to compare the quality of SWCNT films with different thicknesses a figure of merit [4]:

$$K=\frac{1}{R_{s}A}\left[\Omega^{-1}\right]$$

or equivalent sheet resistance at T = 90% calculated as:

$$R_e = \frac{1}{Klg(10/9)} [\Omega/sq.]$$

can be used. A is a light absorbance at 550 nm. The optical spectra were measured using PerkinElmer LAMBDA 950 spectrophotometer in the range from 200 to 2500 nm. The sheet resistance was measured by a 4-probe method using Agilent 34410A and needles separated with a distance of 1 mm. A and R_s of pristine and doped SWCNT films were respectively measured after densification by acetonitrile (CH₃CN) and after doping by a 15 mM AuCl₃ solution in CH₃CN [11]. All values of the sheet resistances (R_s and R_e) of various films are given for CH₃CN densified films (without doping) unless otherwise specified.

3. Experimental results and discussion

3.1. The effect of H₂ addition to CO system

An addition of C_2H_4 into the system at high temperatures (above 900 °C) results in its decomposition and therefore in contamination of the catalyst particles by an excessive amount of the released carbon [18]. Accordingly, in order to enable an active mechanism for the suppression of the C_2H_4 decomposition usually a certain amount of hydrogen is added [19,20]. First, we investigated the effect of H_2 alone introduced into the system apart from the additional carbon source.

It is worth noting that the thickness of the SWCNT films collected is proportional to the optical absorbance [4]. It was found that hydrogen supplement up to 2% had a minor effect on the yield of SWCNTs determined on the basis of absorbance of samples collected during 20 min. However, further increase in the H₂ concentration (to 14.6 vol.%) led to the decrease in the SWCNT yield by a factor of two (Figs. 1 and 2a). At the same time, the quality of SWCNTs, assessed on the basis of the ratios of *G* and D Raman intensities (Fig. S1), was improved at higher hydrogen concentrations (Fig. 2b). As one can also see from the figure, the introduction of hydrogen into the system did not affect the RBM mode of the SWCNTs. Similar results were obtained on the basis of optical spectroscopy measurements, the samples produced with various H_2 concentrations revealed insignificant change in



Fig. 1 – Optical spectroscopy measurements of the samples produced in pure CO system and by adding hydrogen. The samples were produced at 900 °C. (A color version of this figure can be viewed online.)

the SWCNT diameters (Fig. 1). Fitting SWCNT diameter distribution by Gaussian function showed that samples contained two major components: tubes with a diameter around 0.9 and 1.3 nm. (Table S1).

The equivalent sheet resistance of the SWCNT films decreased from $R_e = 2380$ to about 1000 Ω /sq. (Fig. 2c), when 1–2% of H₂ was added to the CO flow. Further increase in the H₂ concentration resulted in the increase of the sheet resistance of the produced SWCNT films and can be explained by etching of released carbon on the surface on catalyst particles. This might reduce the rate of the SWCNT formation and therefore decrease the length of the SWCNTs.

3.2. The effect of C₂H₄ addition to CO-H₂ system

As was mentioned above C_2H_4 without H_2 almost completely decomposes in the reactor at high temperatures. We found that the addition of C_2H_4 even in small quantities (0.2 vol.%) to pure CO resulted in SWCNT films with conductivity close to the insulator. SWCNTs were covered with a thick layer of amorphous carbon and organic byproducts of the hydrocarbon decomposition (Fig. 3a). In fact, first, SWCNTs grew at lower temperature due to the CO disproportionation reaction. Afterwards, at higher temperatures C_2H_4 starts to decompose on the surface of the synthesized SWCNTs. An addition of hydrogen at the concentration of 14.6% into the system allowed us to produce high quality SWCNTs as presented in Fig. 3b.

The influence of the C₂H₄ concentration in the gaseous mixture on the equivalent sheet resistance of the SWCNT films produced at 900 and 1100 °C at the hydrogen concentration of 14.6% is shown in Fig. 4. As can be seen the introduction of C₂H₄ leads to a significant decrease of the sheet resistance at both reaction temperatures. R_e respectively dropped from 1909 and 1709 Ω /sq. to 291 and 358 Ω /sq. at 900 and 1100 °C. The optimum C₂H₄ concentrations in the CO–H₂ system were found to be 6–7 cm³/min (about 1.3 vol.%) at 900 °C and 3–4 cm³/min (about 0.7%) for 1100 °C.

As was mentioned above the maximum temperature for the growth of SWCNTs in the atmosphere of pure CO was



Fig. 2 – The effect of hydrogen concentration on (a) optical absorbance (at 550 nm) of SWCNT films collected during 20 min. (b) Raman intensity G/D ratio of the samples. (c) Equivalent sheet resistance of the samples from two different experimental sets. The samples were produced at 900 °C. (A color version of this figure can be viewed online.)

around 900 °C. At higher temperatures SWCNTs do not grow and as a result films comprising short SWCNTs possess very high sheet resistance of R_e = 3500 and 7500 Ω /sq. for tubes respectively produced at 900 and 1100 °C. As could be



Fig. 3 – TEM images of the as-produced SWCNT samples synthesized by adding 2.5 cm³/min of C₂H₄ (0.5%) to (a) pure CO system and (b) CO-H₂ system.



Fig. 4 – The dependence of equivalent resistance on the C_2H_4 flow at 900 and 1100 °C. (A color version of this figure can be viewed online.)

concluded from the results presented in Figs. 2c and 4 the presence of H_2 and mixture of H_2 and C_2H_4 allowed us to grow SWCNTs even at higher temperatures. This can be explained by switching the carbon source from CO (Boudouard reaction) at lower temperatures to C_2H_4 at higher temperatures: $C_2H_4 \iff 2C_{(s)} + 2H_2$. An addition of hydrogen into the system might also introduce another reaction, which releases the carbon needed for the synthesis of SWCNTs: $H_2 + CO \iff C_{(s)} + H_2O$.

Raman spectra of the samples collected in the presence of C_2H_4 confirmed the production of high quality SWCNTs (Fig. 5a). As can be seen from the spectra the intensity of the RBM peaks corresponding to small diameter tubes increases with increasing the concentration of C_2H_4 in the system. This was confirmed by the optical absorbance measurements (Fig. 5b). We plotted the diameter distribution of the samples (Fig. S2), from which one can clearly see the change in the fraction of the SWCNT diameters (0.9 and 1.3 nm). Quantification of the diameter distribution of SWNTs was done on the basis of UV-vis-NIR spectra of SWCNT films according to the procedure described elsewhere [21]. The results of fitting of the diameter distributions for the samples



Fig. 5 – (a) Raman spectra and (b) optical absorbance of the SWCNTs produced in the CO – H_2 system (14.6% of H_2) at different concentrations of C_2H_4 . Samples were collected at 900 °C. (A color version of this figure can be viewed online.)

with variation of $C_2 H_4$ concentration are presented in Table S1.

As was mentioned above the length of individual tubes as well as bundles [22] are the limiting parameters for the conductivity of randomly oriented SWCNT network, since

they determine the number of intersections between tube and bundles [23,24]. In order to compare this dimension effect on the network conductivity we measured the statistics of the bundle length on the basis of SEM images of SWCNTs produced in the CO-H₂ and CO-C₂H₄-H₂ systems. As can be seen from Fig. 6a the mean bundle length increases from 7.0 to 17 μ m by adding C₂H₄ into the CO-H₂ system. It is worth noting that in the C₂H₄ presence the length of the SWCNT bundles was up to 45 µm (about 40% of all bundles have lengths from 20 to 45 μm). These numbers are to be compared to the bundle length of only $3.4 \,\mu m$ of the SWCNTs obtained in pure CO system. These might explain the drastic equivalent sheet resistance decrease from 3500, 1000 to 291 Ω /sq. for the SWCNT networks comprising the SWCNTs of 3.4, 7.0 and 17 µm and emphasize the superiority of double carbon source systems for the synthesis of SWCNTs.

3.3. The effect of temperature variation

To clarify the temperature effect on the properties of SWCNT films with a double carbon source system, we conducted a series of experiments in the range from 700 to 1100 °C at a fixed gas composition: CO–H₂ system with 1.26% C₂H₄. As can be seen from Fig. 7, the equivalent sheet resistance dropped down by a factor of 5, when the synthesis temperature increased from 700 to 900 °C. Further temperature increase does not practically affect the optoelectronic performance of the SWCNT films.

The yield of the SWCNTs, assessed from optical absorbance measurements, is increased and about 7 times higher for the samples produced at 1100 °C, when compared to the SWCNTs synthesized at 900 °C. This significant increase in the yield can be attributed to greater chemical decomposition rate of the C_2H_4 at higher temperatures. It should be noted that for the pure CO system maximum yield of the SWCNTs is observed at around 880 °C [13]. By adding the second carbon source we were able to prolong the carbon feeding onto catalyst by switching from CO disproportionation to C_2H_4 decomposition and to enhance the growth and therefore the length of the SWCNTs.

Therefore, by increasing the temperature at a certain gas composition in the reactor we were able to solve the problem



Fig. 7 – The optical absorbance (at 550 nm) and equivalent sheet resistance of SWCNTs collected during 20 min. (A color version of this figure can be viewed online.)

of the quality and quantity trade-off between the amount of produced SWCNTs and optoelectrical performance.

3.4. Doping of SWCNT films

In our previous paper [4] we demonstrated the state-of-theart optoelectrical performance ($R_e = 110 \Omega/sq.$) of the SWCNTs produced in a semi-industrial reactor with a longer residence time for the SWCNT growth. That number was afterwards improved to 84 $\Omega/sq.$ at 90% transmittance [5]. Those results were obtained with SWCNTs produced by CO disproportionation reaction and the film were densified and doped by HNO₃ and NO₂. However, these did not lead to satisfactory time stability of the doped SWCNTs. Usually, the sheet resistance of the SWCNTs starts to increase after the doping experiments and reaches about 80–90% of the initial pristine value after 1–2 months depending on the storage conditions.

Here, in order to enhance doping and to improve the stability we have applied the method described in [11,25]. SWCNTs were first densified with acetonitrile and subsequently treated with 15 mM AuCl₃ solution in acetonitrile. Afterwards, the film was washed from the excess amount of the gold salt and dried at ambient conditions.



Fig. 6 – (a) Effect of C_2H_4 addition (1%) to CO- H_2 system (14.6% of H_2) on SWCNT bundle length distribution; (b) SEM image of SWCNTs produced with C_2H_4 . Samples were collected at 900 °C. (A color version of this figure can be viewed online.)

These allowed us to obtain transparent conductive films with the sheet resistance as low as 73 Ω /sq. at 90%. It is worth noting that the stability of the film was significantly improved: the AuCl₃ doped SWCNT films remained their conductivity even after 1 month ambient condition storage. Therefore, the laboratory synthesis reactor by optimizing the carbon source composition allowed us to produce the SWCNT films with an excellent optoelectrical performance even better than the semi-industrial scaled-up reactor [26].

4. Conclusions

To efficiently use the reactor space and to enhance the growth of SWCNTs from CO, we introduced in the reactor the second carbon source (C_2H_4) together with H_2 (to suppress the noncatalytic decomposition of the hydrocarbon). Therefore, at temperatures below 900 °C CO is the main carbon source, while at higher temperatures decomposition of C₂H₄ is predominant. The gas composition change in the aerosol CVD reactor allowed us to increase the length of the SWCNT bundles from 3.4 μ m (pure CO system), via 7.0 μ m (CO-H₂ system) to 17 μ m by adding C₂H₄ at 900 °C. As a result, we observed the significant decrease in the sheet resistance at 90% transmittance from 3500 and 7500 Ω /sq. for pure CO system via 1909 and 1709 Ω /sq. for CO–H₂ system to 291 and 358 Ω /sq. in the presence of C₂H₄ at 900 and 1100 °C, respectively. High temperature synthesis with two carbon sources allowed us to prolong the carbon feeding onto catalyst by switching from CO disproportionation to C₂H₄ decomposition. The yield of the SWCNTs was increased about 7 times at 1100 °C, when compared to 900 °C, preserving the optoelectrical performance of the SWCNT film. Doping of the film with AuCl₃ solution in CH₃CN allowed us to create the transparent conductive films with the sheet resistance as low as 73 Ω /sq. with T 90%.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.carbon. 2014.06.057.

REFERENCES

 Yu M-F, Files BS, Arepalli S, Ruoff RS. Tensile loading of ropes of single wall carbon nanotubes and their mechanical properties. Phys Rev Lett 2000;84(24):5552.

- [2] Lau AK-T, Hui D. The revolutionary creation of new advanced materials – carbon nanotube composites. Compos B 2002;33(4):263–77.
- [3] Sun D-M, Timmermans MY, Nasibulin AG, Kauppinen EI, Kishimoto S, Mizutani T, et al. High-performance carbon nanotube thin-film transistors and logic circuits on flexible substrate. Nat Nanotechnol 2011;6(3):156–61.
- [4] Kaskela A, Nasibulin AG, Timmermans MY, Aitchison B, Papadimitratos A, Tian Y, et al. Aerosol synthesized SWCNT networks with tuneable conductivity and transparency by dry transfer technique. Nano Lett 2010;10(11):4349–55.
- [5] Nasibulin AG, Kaskela A, Mustonen K, Anisimov AS, Ruiz V, Kivisto S, et al. Multifunctional free-standing single-walled carbon nanotube films. ACS Nano 2011;5(4):3214–21.
- [6] Nasibulin AG, Moisala A, Brown DP, Jiang H, Kauppinen EI. A novel aerosol method for single walled carbon nanotube synthesis. Chem Phys Lett 2005;402(1–3):227–32.
- [7] Nasibulin AG, Shandakov SD. Aerosol synthesis of carbon nanotubes. In: Agranovski I, editor. Aerosols: science and technology. Weinheim: Wiley-VCH; 2010. p. 65–89.
- [8] Tian Y, Timmermans MY, Partanen M, Nasibulin AG, Jiang H, Zhu Z, et al. Growth of single-walled carbon nanotubes with controlled diameters and lengths by an aerosol method. Carbon 2011;49(14):4636–43.
- [9] Znidarsic A, Kaskela A, Laiho P, Gaberscek M, Ohno Y, Nasibulin AG, et al. Spatially resolved transport properties of pristine and doped single-walled carbon nanotube networks. J Phys Chem C 2013;117(25):13324–30.
- [10] Zhang M, Fang S, Zakhidov AA, Lee SB, Aliev AE, Williams CD, et al. Strong, transparent, multifunctional, carbon nanotube sheets. Science 2005;309(5738):1215–9.
- [11] Kim SM, Kim KK, Jo YW, Park MH, Chae SJ, Duong DL, et al. Role of anions in the AuCl₃-doping of carbon nanotubes. ACS Nano 2011;5(2):1236–42.
- [12] Nasibulin AG, Queipo P, Shandakov SD, Brown DP, Jiang H, Pikhitsa PV, et al. Studies on mechanism of single-walled carbon nanotube formation. J Nanosci Nanotech 2006;6(5):1233–46.
- [13] Anisimov AS, Nasibulin AG, Jiang H, Launois P, Cambedouzou J, Shandakov SD, et al. Mechanistic investigations of singlewalled carbon nanotube synthesis by ferrocene vapor decomposition in carbon monoxide. Carbon 2010;48(2):380–8.
- [14] Baker RTK, Harris PS. Formation of filamentous carbon. Chem Phys Carbon 1978;14:83.
- [15] Nasibulin AG, Pikhitsa PV, Queipo P, Choi M, Kauppinen EI. Investigations of mechanism of carbon nanotube growth. Phys Status Solidi B 2006;243(13):3095–100.
- [16] Moisala A, Nasibulin AG, Shandakov SD, Jiang H, Kauppinen EI. On-line detection of single-walled carbon nanotube formation during aerosol synthesis methods. Carbon 2005;43(10):2066–74.
- [17] Moisala A, Nasibulin AG, Brown DP, Jiang H, Khriachtchev L, Kauppinen EI. Single-walled carbon nanotube synthesis using ferrocene and iron pentacarbonyl in a laminar flow reactor. Chem Eng Sci 2006;61(13):4393–402.
- [18] Moisala A, Nasibulin AG, Kauppinen EI. The role of metal nanoparticles in the catalytic production of single-walled carbon nanotubes – a review. J Phys 2003;15(42):3011–35.
- [19] Saito T, Ohshima S, Okazaki T, Ohmori S, Yumura M, Iijima S. Selective diameter control of single-walled carbon nanotubes in the gas-phase synthesis. J Nanosci Nanotechnol 2008;8(11):6153–7.
- [20] Rakov EG, Anoshkin IV, Khung N, Saraev PV, Malykh AV, Nguen Man' T, et al. Obtainment and prospects for the application of thin, multiwalled carbon nanotubes. Theor Found Chem Eng 2008;42(5):595–8.
- [21] Tian Y, Jiang H, Pfaler JV, Zhu Z, Nasibulin AG, Nikitin T, et al. Analysis of the size distribution of single-walled carbon

nanotubes using optical absorption spectroscopy. J Phys Chem Lett 2010;1(7):1143–8.

- [22] Mustonen K, Susi T, Kaskela A, Laiho P, Tian Y, Nasibulin AG, et al. Influence of the diameter of single-walled carbon nanotube bundles on the optoelectronic performance of dry-deposited thin films. Beilstein J Nanotechnol 2012;3:692–702.
- [23] Nirmalraj PN, Lyons PE, De S, Coleman JN, Boland JJ. Electrical connectivity in single-walled carbon nanotube networks. Nano Lett 2009;9(11):3890–5.
- [24] Sun J, Wang R. Carbon nanotube transparent electrode. In: Suzuki S, editor. Syntheses and Applications of Carbon Nanotubes and Their Composites. InTech; 2013. p. 313–35.
- [25] Kim KK, Bae JJ, Park HK, Kim SM, Geng H-Z, Park KA, et al. Fermi level engineering of single-walled carbon nanotubes by AuCl₃ doping. J Am Chem Soc 2008;130(38):12757–61.
- [26] Tian Y, Nasibulin AG, Aitchison B, Nikitin T, Pfaler JV, Jiang H, et al. Controlled synthesis of single-walled carbon nanotubes in an aerosol reactor. J Phys Chem C 2011;115(15):7309–18.