INVITED REVIEW PAPER

Carbon nanotube yarns

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Abstract–A CNT yarn is a collection of interlocked CNTs which form a long and continuous fiber of macroscopic scale. CNT yarns of more than a kilometer are now available so that they have been drawing ever-growing attention from the scientific community. In principle, CNT yarns can inherit the excellent electrical, mechanical and chemical properties of CNTs provided they are produced perfectly. In this perspective review, the production methods of CNT yarns are extensively investigated and reported in detail. Although CNT yarns have a great potential to revolutionize our future, it can only be possible by improving their essential material properties such as tensile strength and edectrical conductivity.

Key words: Carbon Nanotube, Fiber, Yarn

INTRODUCTION

Since their introduction, carbon nanotubes (CNTs) have been one of the representative materials of nanotechnology. Their unique electronic and mechanical properties have created widespread interest throughout many different fields of science, resulting in an avalanche of publications. Proposed applications of CNTs include semiconductors, interconnectors, field emitters, batteries, supercapacitors and composites, to name a few. Some of the important applications of CNTs are classified based on the major property concerned, and listed in Table 1 with the authors' personal expectations.

The main roadblock in the applications taking advantage of CNTs' electronic properties is the slow progress in the bandgap engineering of single-walled CNTs (SWCNTs). The bandgap of a SWCNT is a strong function of the chirality and diameter of the SWCNT. We are still unable to mass-synthesize SWCNTs with identical chirality and diameter, thus identical bandgap, at the moment of this review paper. Recent progress in CoMoCat may lead us to this tough-to-achieve goal in the years to come. On the other hand, the applica-

tions using the high surface area of CNTs are mainly hampered by the not-so-great performance of CNTs. This fact, however, is not surprising because the surface area of CNTs is not larger than the other porous carbon materials such as activated carbons or activated carbon fibers. Therefore, the industrial applications of CNTs are expected to be realized earlier in the remaining two application areas (i.e., electrical property and mechanical property) than the above-mentioned application areas. In fact, CNTs have already been synthesized in the amount of hundred tons per year for these purposes as shown in Table 2.

The excellent properties of CNTs became no more unique with the introduction of graphene. Almost every property of a CNT is shared by graphene because a SWCNT is actually a rolled-up graphene sheet. Thus, the applications formerly proposed for CNTs are equally open to graphenes. In fact, some applications utilizing large surface area are better suited for graphenes than CNTs in the sense that a CNT only uses one surface of a graphene sheet.

There is a fundamental difference between CNTs and graphenes, though they are almost identical in many respects. A CNT can be

Table 1. Application of CNTs

| CNT applications	Type of merits	Outstanding problems	Type of problems	Future opportunity*
Transistor	Electronic	Bandgap engineering	Synthesis	Distant
Sensor		Selectivity	Surface chemistry	Near
Interconnector	Electrical	Fabrication	Compatibility	Near
Field emitter		Fabrication	Competing technology	Imminent
Energy absorbing composites	Mechanical	Homogeneous distribution	Processing	Imminent
Tensile strength composites		Tensile strength	Performance	Near
Hydrogen storage	Surface area	Capacity	Performance	Distant
Supercapacitor		Cost	Market	Near
Battery		Capacity	Minor importance	Distant

*Personal expectations

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Table 2. Commercial production of CNTs

Company	Capacity
NCT	MWCNT: 20-30 ton/yr ('07)
Showa denko	MWCMT: 400 ton/yr ('10)
GSI creos	MWCNT: 40-50 ton/yr ('03);
	Cup-shaped CNT: 5 ton/yr ('06)
Nikkiso	SWCNT, MWCNT: 4 ton/yr ('03)
Shinshen nanotech	SWCNT: 2 ton/yr ('05);
	MWCNT: 10 ton/yr ('05)
Hyperion catalysis	MWCNT: >200 ton/yr ('03)
Unidyme	SWCNT: 2 ton/yr ('03)
Nanocyl	MWCNT: 400 ton/yr ('10)
Bayer	MWCNT: 60 ton/yr ('07)
	3,000 ton/yr ('12)
Tomas swan	SWCNT: 1 ton/yr ('06)
Arkema	MWCNT: 10 ton/yr ('07)
	400 ton/yr ('11)
C-Nano	MWCNT: 3,000 ton/yr plant design ('09)

considered as a 1-dimensional (1D) material, while a graphene sheet is a 2-dimensional (2D) material. It is naturally expected that CNTs are a better candidate for the applications which require 1D geometry than graphenes, and vice versa. The obvious prerequisite for 1D applications of CNTs is our ability to prepare long CNTs. Although synthesis of ultralong SWCNTs (tens of centimeters) was reported earlier with a limited quantity, industrial scale applications of these ultralong SWCNTs are still far from reality.

Since the large scale synthesis of long CNTs is quite difficult, alternative routes to make long CNT fibers have been devised in the last decade. An outstanding example is so-called CNT yarns (or fibers). A CNT yarn is a long, continuous, interlocked CNTs [Wikipedia], same as the way we make a rope with straws. We can circumvent the major "shortcoming" of CNTs by making long CNT yarns out of short CNTs. Fig. 1 is the SEM image of the CNT yarn produced in our laboratory. CNT yarns of more than a kilometer are now available, and this is why CNT yarns have been drawing ever-growing attention from carbon scientists since their introduc-
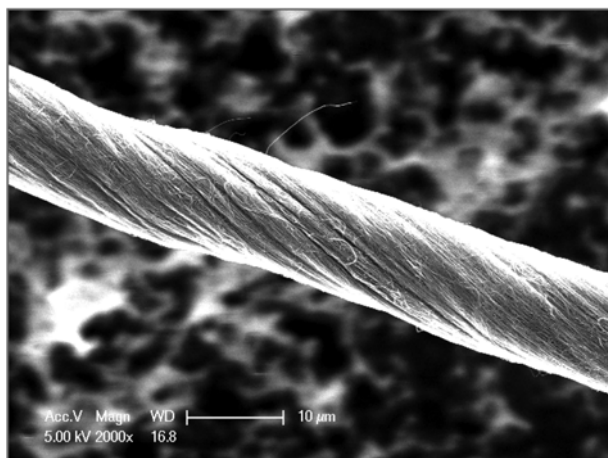
Fig. 1. SEM image of a CNT yarn.
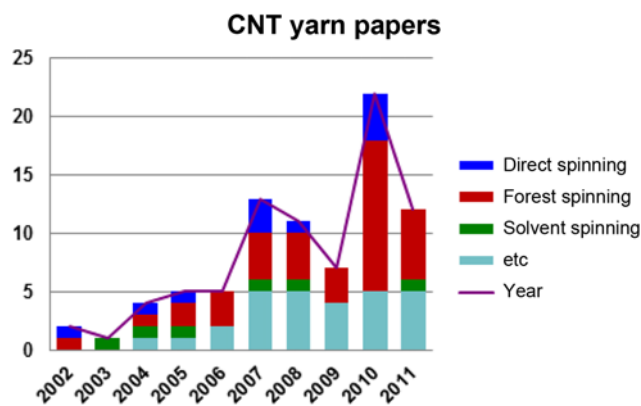
Fig. 2. Journal publications of CNT yarns.

tion in 2002. Journal publications on CNT yarns are graphed in Fig. 2 with rough classification of production methods.

PRODUCTION OF CNT YARNS

The reported production methods of CNT yarns can mainly be classified as three different categories: forest spinning, direct spinning and solution spinning. Each method has its own merits and demerits, and has been progressing neck and neck. Since the solution spinning produces composite yarns of CNTs and polymers, they are not considered in this review.

1. Spinning from a CNT Forest ("Forest Spinning")

CNT yarns can be produced from a CNT forest, which is a large number of vertically aligned CNTs on a substrate, typically a silicon wafer. The synthesis conditions of CNT forests and the details of produced yarns in published papers are summarized in Table 3.

The forest spinning method was first reported in 2002 by the researchers at the Tsinghua University in China [1]. They reported CNT yarns of up to 30 cm long, and demonstrated two applications of their yarns as the filament of a light bulb and the CNT polarizer. The electrical conductivity and the tensile strength of the CNT yarn filament increased after emitting light, indicating the welding of CNTs by resistant heating. Two years later, the researchers at the University of Texas at Dallas introduced "twisting" to CNT yarns, and reported mechanical properties of them [2]. The Los Alamos National Laboratory group joined this race in 2006 [4], followed by the CSIRO Textile & Fiber Technology group of Australia in 2007 [7]. The Shizuoka University group in Japan introduced "chloride-mediated" chemical vapor deposition to synthesize their CNT forest in 2008 [11], but the main characteristics of the forest spinning technology remained unchanged until now.

The forest spinning is a two-step method in which the first step is the growth of a CNT forest, and the second step is the drawing of CNT yarns from the CNT forest. Once the CNTs at the edge of a CNT forest are pulled out, the neighboring CNTs are consecutively pulled out, forming a long, continuous CNT fiber (or ribbon). Fig. 3 shows the CNT forest synthesized on a silicon wafer and the CNT fiber pulled out from the forest. Twisting of this long CNT fiber can be applied to obtain an interlocked CNT yarn as shown in Fig. 1. One of the advantages of the forest spinning is the decoupling of CNT synthesis and yarn drawing. Geometrical parameters of CNTs

Table 3. The synthesis conditions of CNT forests and the details of produced yarns in published papers

Year	CVD method	Catalyst	Thickness of catalyst [nm]	Carbon source (sccm)	Carrier gas (sccm)	Total flow rate (sccm)	Temp. [°C]	CNT diameter (nm)	Height of CNT array [mm]	CNT yarn strength [GPa]	CNT yarn stiffness [GPa]	Conductivity [10^4 S/m]	Ref.
						Reaction conditions					Results		
2002	CVD	Fe	5	Ethylene	Ar	1000	700	14-18	0.03-0.24	-	-	-	[1]
2204	AP-CVD	Fe	5	Acetylene (5 mol%)	He	580	680	8-15	-	0.15-0.46	-	3	[2]
2005	CVD	Fe	3-5	Acetylene (30)	Ar	330	600-680	-	-	-	-	-	[3]
2006	CVD	Fe	0.3-1	Ethylene (100)	Ar (94%) H_2 (6%)	200	750	6-10	0.5-4.7	1.91-3.3	-	-	[4]
2006	AP-CVD	Fe	3.5-5.5	Acetylene (12)	Ar	437	620-700	-	-	0.564	74	-	[5]
2006	LP-CVD	Fe	3.5-5.5	Acetylene (500)	H_2	550	680-720	-	-	0.564	74	-	[5]
2006	CVD	Fe	5	Ethylene (200)	Ar	500	750	10-15	0.5	-	-	-	[6]
2006	CVD	Fe	1	Ethylene (200)	Ar	500	750	10	1	-	-	-	[6]
2007	CVD	Fe	5	Acetylene (5 mol%)	He	580	680	-	0.3-0.55	0.5-0.7	-	-	[7]
2007	CVD	Fe	10	Ethylene (100)	Ar (94%) H_2 (6%)	200	750	7	0.3-1	1.35-3.3	100-263	-	[8]
2007	LP-CVD	Fe	5	Acetylene (500)	H_2	550	680-720	-	-	-	-	-	[9]
2007	CVD	Fe	1	Ethylene (100)	Ar (94%) H_2 (6%)	200	750	10	0.65	0.17-1.91	89-330	1.7-4.1	[10]
2008	FC-CVD	FeCl$_2$	-	Acetylene	-	-	820	30-50	2.1	-	-	-	[11]
2008	CVD	Fe	-	Ethanol	Ar (94%) H_2 (6%)	-	800-850	23 (Trunk) 39 (Bulb)	-	0.35	-	250	[12]
2008	CVD	Fe	2	Ethylene (150)	Ar (350) H_2 (180)	680	750	~10	1	0.3-0.6	7-30	~5	[13]
2008	AP-CVD	Fe	0.2	Acetylene (30)	Ar (200) H_2 (100)	330	680	6.2	-	-	-	-	[14]
2008	AP-CVD	Fe	3.2	Acetylene (30)	Ar (300) H_2 (100)	430	680	6.8	0.9	-	-	-	[14]
2008	AP-CVD	Fe	5	Acetylene (30)	Ar (300) H_2 (100)	430	660	9.2	0.36	-	-	-	[14]
2009	FC-CVD	FeCl$_2$	-	Acetylene	-	-	820	-	1.5	-	-	-	[15]
2009	CVD	Fe	5	Acetylene (5 mol%)	He	580	680	7.5-8.5	0.3-0.4	0.97-1.4	-	-	[16]
2009	FC-CVD	Ferrocene	-	Ethylene (100)	Ar (95%) H_2 (5%)	700	800	15-80	0.2	-	-	-	[17]
2010	CVD	Fe	3.5-5.5	Acetylene (500)	H_2	550	680-720	-	-	0.63-1.1	48-56	9.1	[18]
2010	AP-CVD	Fe	1	Ethylene (110)	Ar (300) H_2 (500)	910	750	15	3.7	-	-	-	[19]
2010	FC-CVD	Ferrocene (10 g/L in soln.)	-	Cyclohexane (5 ml/h)	Ar (80%) H_2 (20%)	800	810	30-40	0.2-0.7	0.24-0.3	-	-	[20]

Table 3. Continued

				Reaction conditions						Results			
Year	CVD method	Catalyst	Thickness of catalyst [nm]	Carbon source (sccm)	Carrier gas (sccm)	Total flow rate (sccm)	Temp. [°C]	CNT diameter (nm)	Height of CNT array [mm]	CNT yarn strength [GPa]	CNT yarn stiffness [GPa]	Conductivity [10^4 S/m]	Ref.
2010	CVD	Fe	~5	Acetylene (5%)	He	650 (He only)	670	10-15	0.35	0.58	-	-	[21]
2010	CVD	Fe	2.3	Acetylene (5%)	He	650 (He only)	670	10	0.4	-	-	-	[22]
2010	CVD	Fe	2	Acetylene (7v%)	Ar (63v%) H$_2$ (30v%)	800	700	11.1	-	0.3	-	3.5	[23]
2010	Py-CVD	Ferrocene (0.1 g)	-	Polypropylene (2.0 g)	Ar (500) H$_2$ (30)	530	800	22.6-36	0.5	-	-	-	[24]
2010	AP-CVD	Fe	5	Acetylene (5 mol%)	He	580	680	~12	0.16-0.39	~0.8	-	-	[25]
2010	CVD	Fe	0.8	Ethylene	Ar H$_2$ O$_2$	-	750	-	-	~1.4	~100	-	[26]
2011	CVD	Fe	-	Ethylene	Ar H$_2$	-	660-750	6	0.26	1.17	53.5	-	[27]
2011	CVD	Fe	2	Acetylene (25)	Ar	1000	680	6.6-10.5	0.245-0.26	0.4-0.8	-	-	[28]
2011	CVD	Fe	2	Acetylene (25)	Ar H$_2$ (25)	1025	680	8.7-10.6	0.21-0.38	0.6-0.85	-	-	[28]
2011	CVD	Fe	2.3	Acetylene (100)	He (4000) H$_2$ (100)	4200	-	10	0.45	0.46	-	3	[29]
2011	CVD	Fe	1-3	Acetylene (50)	Ar (750) H$_2$ (100)	900	700	~9	0.35	-	-	-	[30]
2011	FC-CVD	FeCl$_2$	-	Acetylene	-	-	820	-	2.4	-	-	-	[31]

CVD: Chemical vapor deposition, AP-CVD: Atmospheric pressure CVD, LP-CVD: Low pressure CVD, FC-CVD: Floating catalyst CVD, Py-CVD: Pyrolysis CVD

such as length, diameter, straightness, and the distance between CNTs can be controlled independently and accurately, so that the effects of these parameters on the production and the properties of CNT yarns can be investigated easily. The critical drawback of forest spinning is poor productivity. It is a batch process: the maximum length of a continuous CNT yarn is limited by the amount the CNTs synthesized on a substrate. An effort to remove this fundamental limitation was reported by introducing a flexible stainless steel substrate which could move like a conveyor belt [23].

Synthesis of CNT forest is now a generic technology, while only a small number of research groups are successful in drawing CNT yarns from CNT forests. This difficulty lies in the fact that not all CNT forests are created equal, and our knowledge is still incomplete on which factor governs the spinnability of a CNT forest. Two different explanations were proposed for the mechanism of the forest spinning. The first model considers that the van der Waals force among parallel CNTs makes continuous pulling of CNTs out of a CNT forest possible ("superalign model") [5]. According to this model, super-aligned CNTs and clean surfaces of CNTs are the most important factors assuring the spinnability of a CNT forest. On the other hand, the second and more recent model proposes that the connecting CNTs between CNT bundles are responsible for the continuous spinning of a CNT yarn from a CNT forest [33]. In this model, the morphology of a CNT forest can be envisioned as that of a string cheese, and the morphological change during the yarn drawing process is quite similar as what happens when we tear a string cheese ("string cheese model"). Fig. 4 conceptually illustrates the main ideas of these two models.

The tensile strengths of CNT yarns produced by the forest spinning are still lower than those of commercial high strength fibers such as Kevlar, Dyneema or carbon fiber. Fig. 5 is an example of the stress-strain curve of the CNT yarns produced from different gaseous carbon sources. Although the maximum tensile strengths of these CNT yarns are not impressive, the maximum strains are surprisingly large compared with other high strength fibers [27]. This is mainly due to the fact that a CNT yarn is not a monolithic fiber,
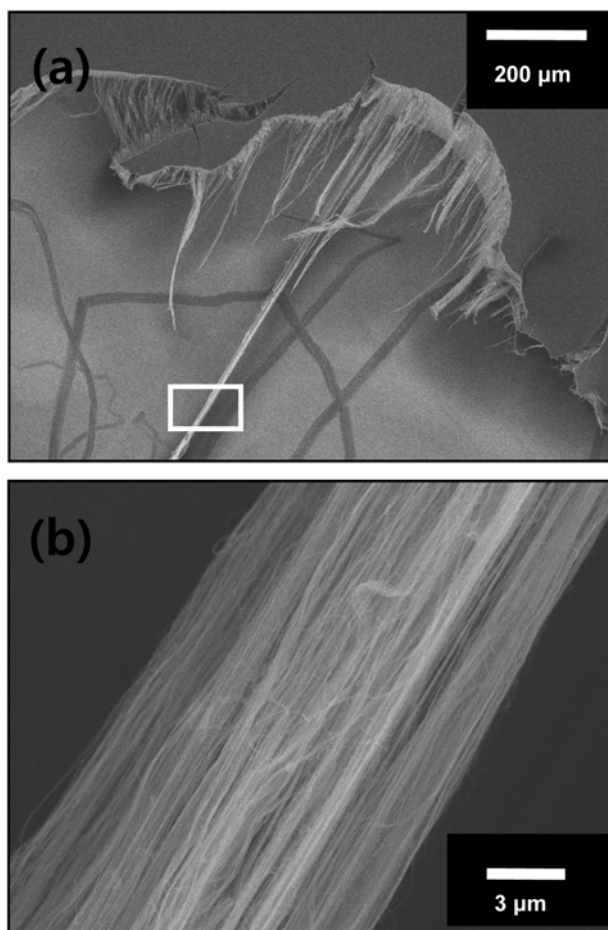
Fig. 3. The forest spinning method (a) a CNT yarn pulled from a CNT forest (b) high magnification image of the region denoted as a white square in (a).

Fig. 4. Illustration of the core concept for forest spinning (a) super-align model [5], and (b) string cheese model [33].

Fig. 5. The stress-strain curve of CNT yarns produced from different gaseous carbon sources. Although the maximum tensile strength of these CNT yarns is not impressive, the maximum strain is surprisingly large compared with other high strength fibers [27].

but actually a collection of many CNTs which have much smaller diameters than a monolithic fiber.

2. Spinning from a CNT Aerogel ("Direct Spinning")

Direct spinning is a one-step method which is capable of continuously producing CNT yarns without length limitation. The synthesis conditions of CNT clusters in the vapor phase and the details of produced yarns in published papers are summarized in Table 4.

The first CNT yarns by the direct spinning were produced by the joint forces of the Tshighua University and the Rensselaer Polytechnic Institute in 2002 [37]. The strands of SWCNTs of almost 20 cm were synthesized by the "enhanced vertical floating technique" with n-hexane as a carbon source. The strand had good strength (1.2 GPa) and electrical conductivity ($1.4 \sim 2 \times 10^5$ S/m). The Cambridge group reported their CNT yarns in 2004 with ethanol as a carbon source [38]. They performed a detailed study on the effect of carbon sources on the formation of CNT yarns, and concluded that oxygen-containing carbon sources were necessary to produce continuous CNT yarns. The direct spinning method received great attention in 2007 when the Cambridge group reported the CNT yarns stronger than high performance carbon fibers for the first time [41]. Although the gauge length of the strong CNT yarns was only 1 mm, and the strength greatly decreased with the longer samples, this was a phenomenal event that generated a surge of interest in CNT yarns.
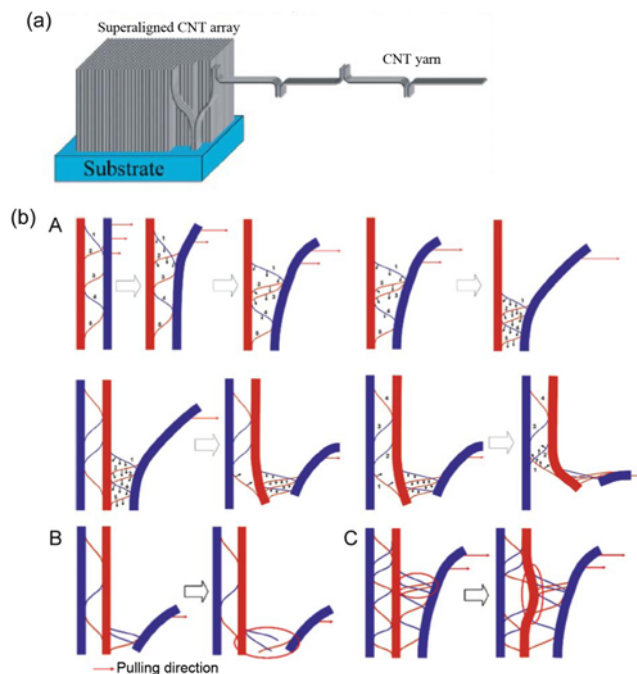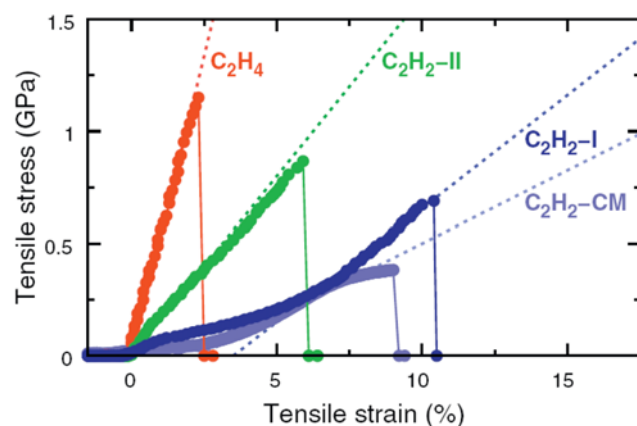
CNTs are synthesized in the vapor phase of a vertical reactor and form a porous cluster similar to "cotton candy." The porosity of this carbon cluster is very high, so that it can be considered as a carbon aerogel. It is also called a "sock" or "stocking" due to its similarity in overall shape. A continuous CNT fiber or ribbon is drawn from this CNT aerogel at the bottom of the reactor. Fig. 6 illustrates the process schematics of the direct spinning and some of the important steps of CNT synthesis in the vapor phase. Fig. 7 shows the CNT yarns produced by the direct spinning. The length of CNT yarns produced by the direct spinning has increased from around 20 cm [37] to more than a km [46] in less than a decade. The obvious advantage of direct spinning is high productivity. It can continuously

Table 4. The synthesis conditions of CNT aerogels and the details of produced yarns in published papers

Year	Reaction conditions						Results of CNT spun yarns				Ref.
	Catalyst weight percent [wt%] (Fe/S)	Carbon source	Reactant injection rate [ml/h]	Carrier gas	Carrier gas flow rate [ml/min]	Temp. [°C]	CNT diameter [nm]	CNT yarn strength [GPa]	CNT yarn stiffness [GPa]	Conductivity [10^5 S/m]	
2002	0.018 (g/ml)/0.4	n-Hexane	30	H_2	250	1150	1.1-1.7	1.2	49-77	1.43-2	[37]
2004	0.23-2.3/1-4	Ethanol	4.8-15	H_2	400-800	1050-1200	1.6-3.5 (SW)/ 30 (MW)	0.1-1.0	-	8.3	[38]
2005	0.009-0.022 (atom%)/ 0.01-0.03 (atom%)	Ethanol, ethylene - Glycol hexane	2-7.5	H_2 or H_2/Ar	400-1000	1180	-	0.14-1.46	5-30	-	[39]
2007	0.23-2.3/1-4	Ethanol	4.8-15	H_2	400-800	1050-1200	4-10 (DW)	1.3-8.8	78-357	-	[41]
2007	2.3/1.5	Ethanol	7	H_2	600	1180	15-20	-	-	-	[40]
2007	2.0/0.3	Ethanol	7	H_2	1500	1300	5-10 (DW)	1.2-2.2	65-160	-	[42]
2008	-	-	-	-	-	-	-	1	50	8	[43]
2010	3.1/0.5	Acetone	12	Ar	100-300	1170	1.3-4.6	0.120-0.144 (Film)	-	0.8	[47]
2010	1.6/0.8	Acetone	8	H_2	1000	1170	8-10	0.4-1.25	-	5	[46]
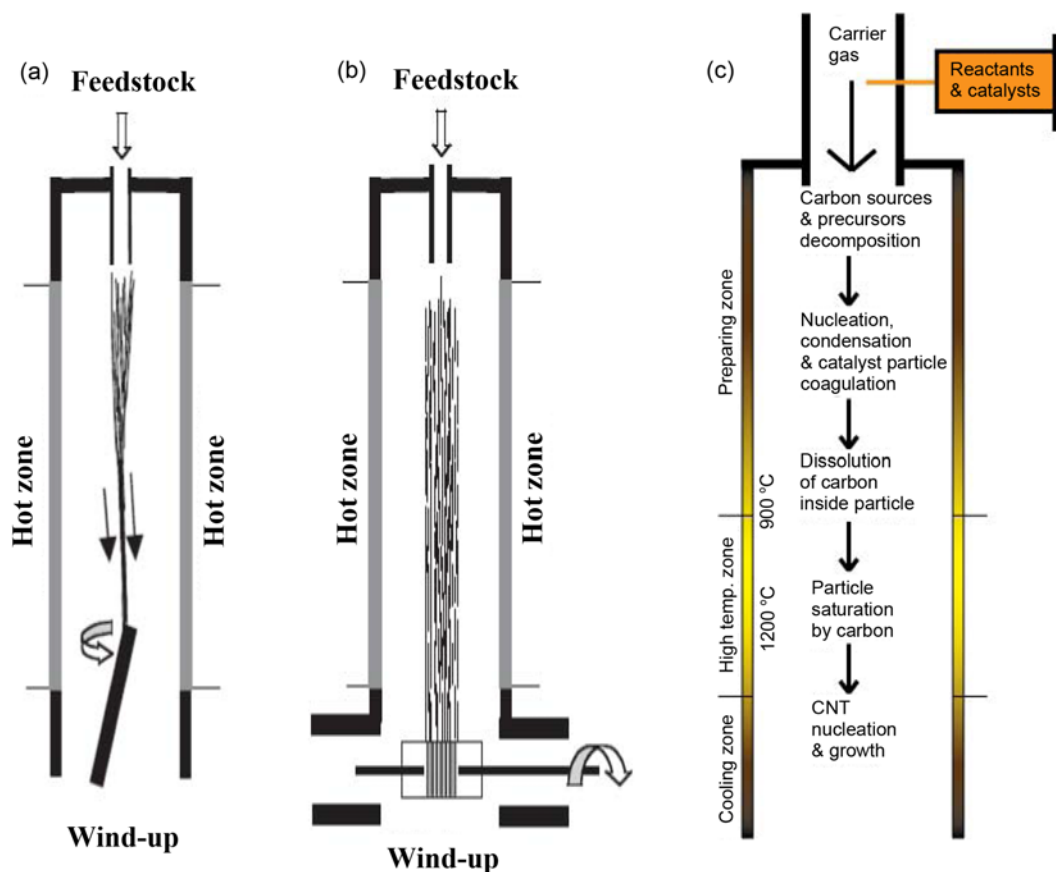
Fig. 6. Process schematics of the direct spinning (a) drawing of a CNT fiber [38], (b) drawing of a CNT ribbon [38], and (c) the important reaction steps of CNT synthesis in the vapor phase [49].

produce CNT yarns or ribbons with high throughput. In theory, we can produce CNT yarns of infinite length, provided the synthesis conditions are maintained. It is expected that stable production of

CNT yarns can only be achieved by the accurate control of the operating conditions, since a continuous and fast production process is generally sensitive to small perturbations in operating conditions.

It should be noted that some CNTs synthesized in the direct spinning method have much larger diameters with smaller number of
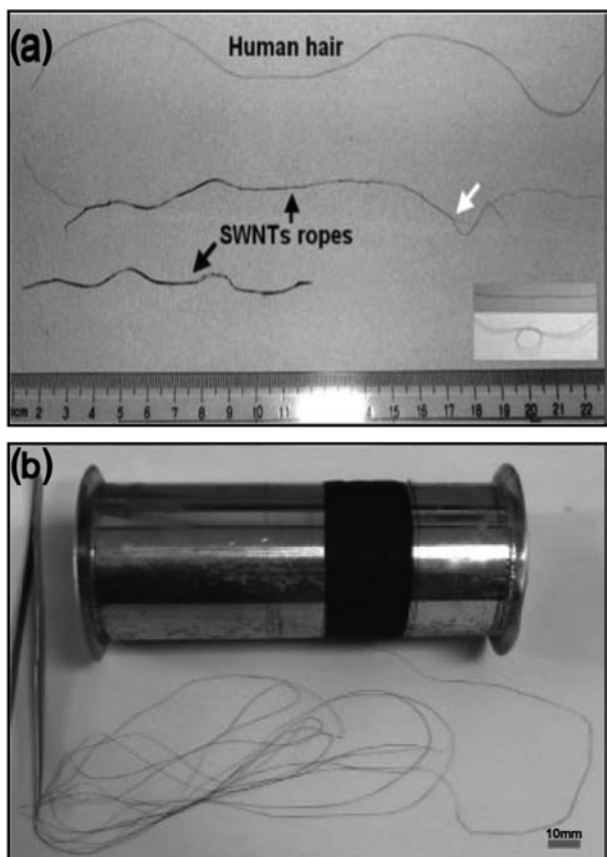

Fig. 7. The CNT yarns produced by the direct spinning. The length of CNT yarns produced by the direct spinning has increased form (a) around 20 cm [37] to (b) more than a km [46].
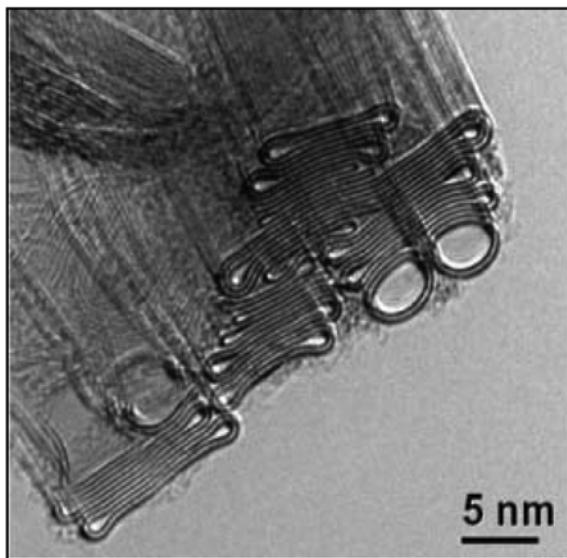

Fig. 8. The morphology of the CNTs synthesized by the direct spinning. Here, the CNTs are mostly double-walled CNTs (DWCNTs), and the collapsed (dog-bone) CNTs have much larger diameter than the un-collapsed (tubular) ones [42].

graphitic walls than the CNTs synthesized by forest spinning. Since these large diameter CNTs do not sustain their tubular shape due to the lack of structural stability, they are collapsed and transformed into the "dog-bone" shape [42]. Fig. 8 shows the TEM image of the CNTs synthesized by the direct spinning. Here, the CNTs are mostly double-walled CNTs (DWCNTs), and it is obvious that the collapsed (dog-bone) CNTs have much larger diameter than the un-collapsed (tubular) ones. When CNTs are collapsed, the contact area between CNTs increases dramatically. This larger contact area makes a CNT yarn much stronger. The strongest CNT yarn ever reported was indeed produced by the direct spinning method. Fig. 9(a) demonstrates that the specific strength of the CNT yarn (fiber) is much higher than those of the commercial high strength fibers [41]. However, such a high strength was obtained with one short sample (1 mm),
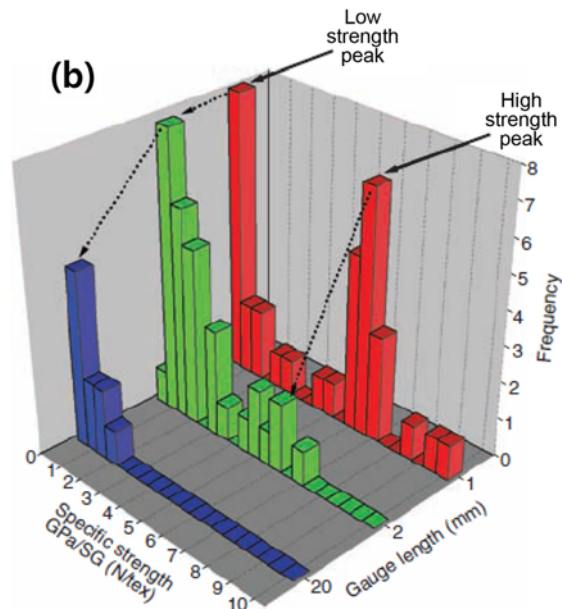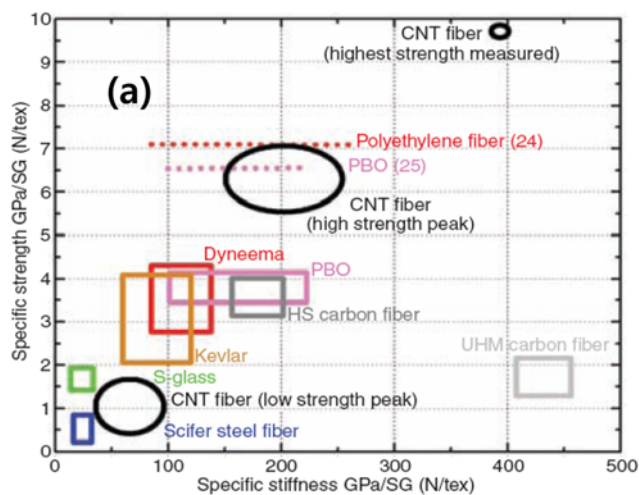

Fig. 9. Specific strength of the CNT yarns (fibers) produced by the direct spinning method [41]. (a) The specific strength of the CNT yarn (fiber) is much higher than that of the commercial high strength fibers. (b) Such a high strength was obtained with one short sample (1 mm), and the average strength decreases with the length of samples.

and the average strength decreases with the length of sample as in Fig. 9(b).

POST-TREATMENT OF CNT YARNS

A strand of CNT fiber consists of thousands of individual CNTs. The van der Waals forces between these CNTs hold them together and are responsible for the strength of the fiber as a monolithic entity. The van der Waals force decreases with the distance between the CNTs, and the strength of a CNT fiber increases with the total contact area among the CNTs. Therefore, compaction of a CNT fiber is an efficient way to increase the strength of the CNT fiber. Compaction of a CNT fiber can be done by adding a solvent to the CNT fiber, then evaporating it. The capillary force attracts adjacent CNTs each other during evaporation. The result is a compacted CNT fiber with much increased linear density [18]. Fig. 10 shows the effect of *in situ* compaction process. The degree of compaction is quite noticeable [41].
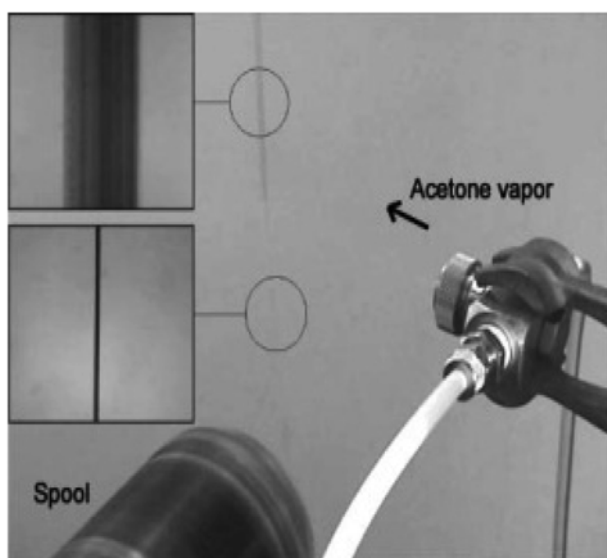

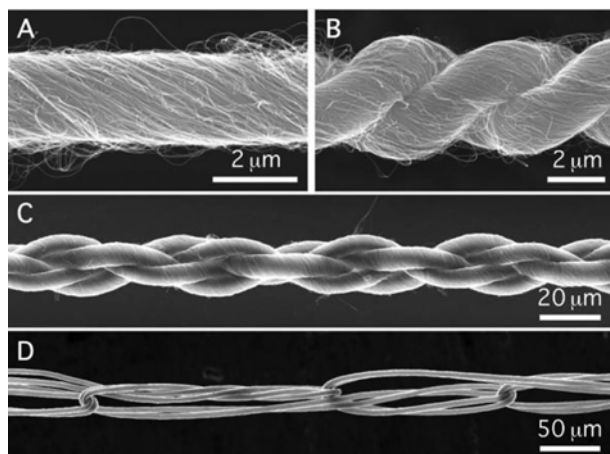Fig. 10. The effect of *in situ* compaction process [41].

Fig. 11. SEM images of (A) single, (B) two-ply, (C) four-ply, and (D) knotted MWCNT yarns [2].

Twisting is the essential process to produce a long yarn from short CNTs. As a CNT fiber (or yarn) is twisted, the distance between the CNTs decreases, and the total contact area between the CNTs increases. Moreover, the CNTs composing the CNT yarn tend to align by the twisting shear force. All these factors affect the strength of a CNT yarn constructively, resulting in a stronger CNT yarn. Fig. 11 shows some examples of twisted CNT yarns [2]. However, twisting with large twisting angles decreases the strength of CNT yarns [18], so that careful optimization of the twisting process is desired.

The strength of a CNT fiber can be improved by introducing a stronger force between CNTs than van der Waals force. In fact, a hydrogen bond is the force acting between the molecules in a Kevlar fiber. Introducing covalent bonds between the CNTs in a CNT yarn may also be possible by applying chemicals and/or heat.

One of the outstanding properties of a CNT is electrical conductivity, and it is expected that CNT yarns can inherit high electrical conductivity. Unfortunately, the electrical conductivities of pure CNT yarns are much smaller than those of metals. Metal doping of CNT yarns could improve the electrical conductivities [50,51], but the goal is yet to be achieved.
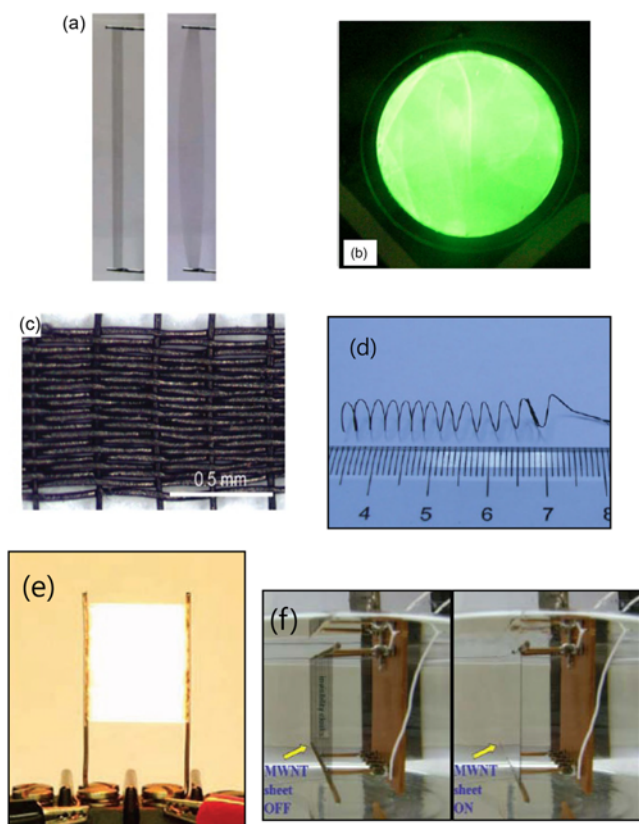
APPLICATIONS OF CNT YARNS

Various applications of CNT yarns have been demonstrated since their introduction in 2002. Table 5 summarizes some of the applications with their references, and some of the demonstrated samples appear in Fig. 12. Applications of CNT yarns can be greatly extended when other materials are incorporated into CNT yarns. A notable example is given in Fig. 13 [30]. Various nanoparticles were sprayed on to the CNT ribbons, and these ribbons are twisted to form the CNT yarns. The produced "biscroll" yarns possess the properties of nanoparticles as well as those of the CNT yarns.

Most of the applications of CNT yarns, however, are not mature, and some of them are better suited to niche markets. Although CNT yarns have a great potential to revolutionize our future, it can only be possible by improving their essential material properties such as tensile strength, electrical conductivity etc. Intensive researches are

Table 5. Demonstrated applications of CNT yarns

Type	Reference
High strength and conductive fibers	54
Artificial muscle	52
Strain sensor	93
TEM nanogrid	89
Field-emission	60. 68, 76, 51
Supercapacitor	90
Flexible touch screens	85
Batteries	91
Invisible material	53
Optical polarizer	1
Light emission	98
Liquid crystal alignment layers	99
Incandescent display	86
Thermal transport	61
Flexible stretchable loudspeakers	87, 88

Fig. 12. Demonstration samples of CNT yarns applications (a) artificial muscle [52], (b) field emitter [60], (c) woven fabric [54], (d) spring [5], (e) light [98], and (f) invisible cloak [53].
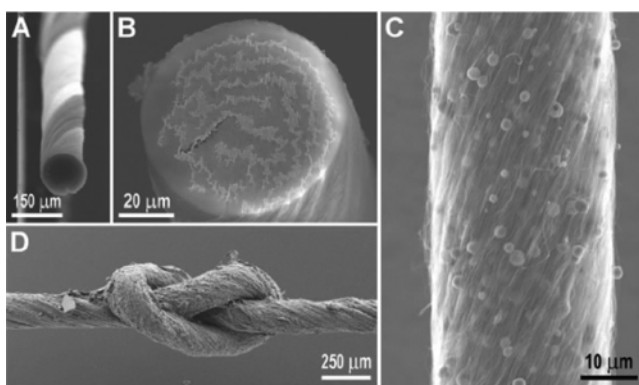
Fig. 13. Bi-scroll yarns [30]. (A) and (B) $Si_3B_4NT@MWNT_{0.2}$ biscrolled yarn, (C) $TiO_2@MWNT_{1.0}$ yarn (D) overhand knot in 95% $LiFePO_4@MWNT_{3.3}$ yarn.

ongoing worldwide, so that major breakthroughs are expected in the years to come.

REFERENCES

1. K. Jiang, Q. Li and S. Fan, *Nature*, **419**, 801 (2002).
2. M. Zhang, K. R. Atkinson and R. H. Baughman, *Science*, **306**, 1358 (2004).
3. K. Liu, K. Jiang, C. Feng, Z. Chen and S. Fan, *Carbon*, **43**, 2850 (2005).

4. Q. Li, X. Zhang, R. F. DePaula, L. Zheng, Y. Zhao, L. Stan, T. G. Holesinger, P. N. Arendt, D. E. Peterson and Y. T. Zhu, *Adv. Mater.*, **18**, 3160 (2006).
5. X. Zhang, K. Jiang, C. Feng, P. Liu, L. Zhang, J. Kong, T. Zhang, Q. Li and S. Fan, *Adv. Mater.*, **18**, 1505 (2006).
6. Q. Li, R. DePaula, X. Zhang, L. Zheng, P. N. Arendt, F. M. Mueller, Y. T. Zhu and Y. Tu, *Nanotechnology*, **17**, 4533 (2006).
7. K. R. Atkinson, S. C. Hawkins, C. Huynh, C. Skourtis, J. Dai, M. Zhang, S. Fang, A. A. Zakhidov, S. B. Lee, A. E. Aliev, C. D. Williams and R. H. Baughman, *Physica B*, **394**, 339 (2007).
8. X. Zhang, Q. Li, T. G. Holesinger, P. N. Arendt, J. Huang, P. D. Kirven, T. G. Clapp, R. F. DePaula, X. Liao, Y. Zhao, L. Zheng, D. E. Peterson and Y. Zhu, *Adv. Mater.*, **19**, 4198 (2007).
9. Y. Wei, K. Jiang, X. Feng, P. Liu, L. Liu and S. Fan, *Physical Review B*, **76**, 045423 (2007).
10. X. Zhang, Q. Li, Y. Tu, Y. Li, J. Y. Coulter, L. Zheng, Y. Zhao, Q. Jia, D. E. Peterson and Y. Zhu, *Small*, **3**, 244 (2007).
11. Y. Inoue, K. Kakihata, Y. Hirono, T. Horie, A. Ishida and H. Mimura, *Appl. Phys. Lett.*, **92**, 213113 (2008).
12. H. Peng, M. Jain, Q. Li, D. E. Peterson, Y. Zhu and Q. Jia, *J. Am. Chem. Soc.*, **130**, 1130 (2008).
13. S. Zhang, L. Zhu, M. L. Minus, H. G. Chae, S. Jagannathan, C.-P. Wong, J. Kowalik, L. B. Roberson and S. Kumar, *J. Mater. Sci.*, **43**, 4356 (2008).
14. K. Liu, Y. Sun, L. Chen, C. Feng, X. Feng, K. Jiang, Y. Zhao and S. Fan, *Nano Lett.*, **8**, 700 (2008).
15. S. Shimizu, M. Okada, Y. Inoue, Y. Neo, H. Kume, T. Aoki and H. Mimura, *Journal of Automation, Mobile Robotics & Intelligent Systems*, **3**, 163 (2009).
16. C. D. Tran, W. Humphries, S. M. Smith, C. Huynh and S. Lucas, *Carbon*, **47**, 2662 (2009).
17. Q. Zhang, J.-Q. Huang, M.-Q. Zhao, W.-Z. Qian and F. Wei, *Appl. Phys. A*, **94**, 853 (2009).
18. K. Liu, Y. Sun, R. Zhou, H. Zhu, J, Wang, L, Liu, S. Fan and K. Jiang, *Nanotechnology*, **21**, 045708 (2010).
19. I. H. Lee, G. H. Han, S. J. Chae, J. J. Bae, E. S. Kim, S. M. Kim, T. H. Kim, H.-K. Jeong and Y. H. Lee, *Nano*, **5**, 31 (2010).
20. Q. Zhang, D.-G. Wang, J.-Q. Huang, W.-P. Zhou, G-H. Luo, W.-Z. Qian and F. Wei, *Carbon*, **48**, 2855 (2010).
21. K. Sears, C. Skourtis, K. Atkinson, N. Finn and W. Humphries, *Carbon*, **48**, 4450 (2010).
22. C. P. Huynh and S. C. Hawkins, *Carbon*, **48**, 1105 (2010).
23. X. Lepro, M. D. Lima and R. H. Baughman, *Carbon*, **48**, 3621 (2010).
24. Z. Yang, Q. Zhang, G. Luo, J.-Q. Huang, M.-Q. Zhao and F. Wei, *Appl. Phys. A*, **100**, 533 (2010).
25. S. Fang, M. Zhang, A. A. Zakhidov and R. H. Baughman, *J. Phys.: Condens. Matter*, **22**, 334221 (2010).
26. L. Zheng, G. Sun and Z. Zhan, *Small*, **6**, 132 (2010).
27. J. Jia, J. Zhao, G. Xu, J. Di, Z. Yong, Y. Tao, C. Fang, Z. Zhang, X. Zhang, L. Zheng and Q. Li, *Carbon*, **49**, 1333 (2011).
28. C. P. Huynh, S. C. Hawkins, M. Redrado, S. Barnes, D. Lau, W. Humphries and G. P. Simon, *Carbon*, **49**, 1989 (2011).
29. M. Musameh, M. R. Notivoli, M. Hickey, I. L. Kyratzis, Y. Gao, C. Huynh and S. C. Hawkins, *Adv. Mater.*, **23**, 906 (2011).
30. M. d. Lima, S. Fang, X. Lepro, C. Lewis, R. O. Robles, J. C. Gonzalez, E. C. Martinez, M. E. Kozlov, J. Oh, N. Rawat, C. S. Haines,

M. H. Haque, V. Aare, S. Stoughton, A. A. Zakhidov and R. H. Baughman, *Science*, **331**, 51 (2011).

31. K. Suzuki, S. Sakakibara, M. Okada, Y. Neo, H. Mimura, Y. Inoue and T. Murata, *Japanese J. Appl. Phys.*, **50**, 01BJ10 (2011).

32. Y. Inoue, Y. Suzuki, Y. Minami, J. Muramatsu, Y. Shimamura, K. Suzuki, A. Ghemes, M. Okada, S. Sakakibara, H. Mimura and K. Naito, *Carbon*, **49**, 2437 (2011).

33. A. A. Kuznetsov, A. F. Fonseca, R. H. Baughman and A. A. Zakhidov, *ACS Nano*, **5**, 985 (2011).

34. C. Zhu, C. Cheng, Y. H. He, L. Wang, T. L. Wong, K. K. Fung and N. Wang, *Carbon*, **49**, 4996 (2011).

35. J. Zhao, X. Zhang, J. Di, G. Xu, X. Yang, X. Liu, Z. Yong, M. Chen and Q. Li, *Small*, **6**, 2612 (2010).

36. Y. Zhang, G. Zou, S. K. Doorn, H. Htoon, L. Stan, M. E. Hawley, C. J. Sheehan, Y. Zhu and Q. Jia, *ACS Nano*, **3**, 2157 (2009).

37. H. W. Zhu, C. L. Xu, D. H. Wu, B. Q. Wei, R. Vajtai and P. M. Ajayan, *Science*, **296**, 884 (2002).

38. Y.-L. Li, I. A. Kinloch and A. H. Windle. *Science*, **304**, 276 (2004).

39. M. Motta, Y.-L. Li, I. Kinloch and A. Windle, *Nano Lett.*, **5**, 1529 (2005).

40. M. Motta, I. Kinloch, A. Moisala, V. Premnath, M. Pick and A. Windle, *Physica E*, **37**, 40 (2007).

41. K. Koziol, J. Vilatela, A. Moisala, M. Motta, P. Cunniff, M. Sennett and A. Windle, *Science*, **318**, 1892 (2007).

42. M. Motta, A. Moisala, I. A. Kinloch and A. H. Windle, *Adv. Mater.*, **19**, 3721 (2007).

43. K. L. Stano, K. Koziol, M. Pick, M. S. Motta, A. Moisala, J. J. Vilatela, S. Frasier and A. H. Windle, *Int. J. Mater. Form*, **1**, 59 (2008).

44. I. S. Fraser, M. S. Motta, R. K. Schmidt and A. H. Windle, *Sci. Technol. Adv. Mater.*, **11**, 045004 (2010).

45. J. J. Vilatela and A. H. Windle, *Adv. Mater.*, **22**, 4959 (2010).

46. X.-H. Zhong, Y.-L. Li, Y.-K. Liu, X.-H. Qiao, Y. Feng, J. Liang, J. Jin, L. Zhu, F. Hou and J.-Y. Li, *Adv. Mater.*, **22**, 692 (2010).

47. J.-M. Feng, R. Wang, Y.-L. Li, X.-H. Zhong, L. Cui, Q.-J. Guo and F. Hou, *Carbon*, **48**, 3817 (2010).

48. J. J. Vilatela, J. A. Elliott and A. H. Windle. *ACS Nano.*, **5**, 1921 (2011).

49. A. Moisala, A. G. Nasibulin and E. I. Kauppinen, *J. Phys.: Condens. Matter*, **15**, S3011 (2003).

50. L. K. Randeniya, A. Bendavid, P. J. Martin and C.-D. Tran, *Small*, **6**, 1806 (2010).

51. Y. Yang, L. Liu, Y. Wei, P. Liu, K. Jiang, Q. Li and S. Fan, *Carbon*, **48**, 531 (2010).

52. A. E. Aliev, J. Oh, M. E. Kozlov, A. A. Kuznetsov, S. Fang, A. F. Fonseca, R. Ovalle, M. D. Lima, M. H. Haque, Y. N. Gartstein, M. Zhang, A. A. Zakhidov and R. H. Baughman, *Science*, **323**, 1575 (2009).

53. A. E. Aliev, Y. N. Gartstein and R. H. Baughman, *Nanotechnology*, **22**, 435704 (2011).

54. K. Liu, Y. Sun, X. Lin, R. Zhou, J. Wang, S. Fan and K. Jiang, *ACS Nano.*, **4**, 5827 (2010).

55. R. M. Sundaram, K. K. K. Koziol and A. H. Windle, *Adv. Mater.*, **23**, 5064 (2011).

56. W. Ma, L. Song, R. Yang, T. Zhang, Y. Zhao, L. Sun, Y. Ren, D. Liu, L. Liu, J. Shen, Z. Zhang, Y. Xiang, W. Zhou and S. Xie, *Nano Lett.*, **7**, 2307 (2007).

57. W. Zhou, J. Vavro, C. Guthy, K. I. Winey, J. E. Fischer, L. M. Ericson, S. Ramesh, R. Saini, V. A. Davis, C. Kittrell, M. Pasquali, R. H. Hauge and R. E. Smalley, *J. Appl. Phys.*, **95**, 649 (2004).

58. H. Huang, C. Liu, Y. Wu and S. Fan, *Adv. Mater.*, **17**, 1652 (2005).

59. P. Liu, Y. Wei, K. Jiang, Q. Sun, X. Zhang, S. Fan, S. Zhang, C. Ning and J. Deng, *Phys. Rev. B*, **73**, 235412 (2006).

60. Y. Wei, D. Weng, Y. Yang, X. Zhang, K. Jiang, L. Liu and S. Fan, *Appl. Phys. Lett.*, **89**, 063101 (2006).

61. A. E. Aliev, C. Guthy, M. Zhang, S. Fang, A. A. Zakhidov, J. E. Fischer and R. H. Baughman, *Carbon*, **45**, 2880 (2007).

62. K. Liu, P. Liu, K. Jiang and S. Fan, *Carbon*, **45**, 2379 (2007).

63. L. Zheng, X. Zhang, Q. Li, S. B. Chikkannanavar, Y. Li, Y. Zhao, X. Liao, Q. Jia, S. K. Doorn, D. E. Peterson and Y. Zhu, *Adv. Mater.*, **19**, 2567 (2007).

64. Z. L. Wang, D. W. Tang, X. B. Li, X. H. Zheng, W. G. Zhang, L. X. Zheng, Y. T. Zhu, A. Z. Jin, H. F. Yang and C. Z. Gu, *Appl. Phys. Lett.*, **91**, 123119 (2007).

65. Q. Li, Y. Li, X. Zhang, S. B. Cikkannanavar, Y. Zhao, A. M. Dangelewicz, L. Zheng, S. K. Doorn, Q. Jia, D. E. Peterson, P. N. Arendt and Y. Zhu, *Adv. Mater.*, **19**, 3358 (2007).

66. E. Joselevich, H. Dai, J. Liu, K. Hata and A. H. Windle, *Topics in Applied Physics*, **111**, 101 (2008).

67. O. Suekane, A. Nagataki, H. Mori and Y. Nakayama, *Appl. Phys. Exp.*, **1**, 064001 (2008).

68. L. Xiao, P. Liu, L. Liu, K. Jiang, X. Feng, Y. Wei, L. Qian, S. Fan and T. Zhang, *Appl. Phys. Lett.*, **92**, 153108 (2008).

69. H. Peng, M. Jain, D. E. Peterson, Y. Zhu and Q. Jia, *Small*, **4**, 1964 (2008).

70. H. Peng. *J. Am. Chem. Soc.*, **130**, 42 (2008).

71. R. J. Mora, J. J. Vilatela and A. H. Windle, *Composites Science and Technology*, **69**, 1558 (2009).

72. Q. Zhang, G.-H. Xu, J.-Q. Huang, W.-P. Zhou, M.-Q. Zhao, Y. Wang, W.-Z. Qian and F. Wei, *Carbon*, **47**, 538 (2009).

73. J. D. W. Madden, *Science*, **232**, 1571 (2009).

74. D. Conroy, A. Moisala, S. Cardoso, A. Windle and J. Davidson, *Chem. Eng. Sci.*, **65**, 2965 (2010).

75. Q. Zhang, M.-Q. Zhao, D.-M. Tang, F. Li, J.-Q. Huang, B. Liu, W.-C. Zhu, Y.-H. Zhang and F. Wei, *Angewandte Chemie*, **122**, 3724 (2010).

76. H.-S. Jang, S. K. Jeon and S. H. Nahm. *Carbon*, **48**, 4019 (2010).

77. I. J. Beyerlein, P. K. Porwal, Y. T. Zhu, X. F. Xu and S. L. Phoenix, *Solid Mechanics and its Applications*, **168**, 211 (2010).

78. J. J. Vilatela, L. Deng, I. A. Kinloch, R. J. Young and A. H. Windle, *Carbon*, **49**, 4149 (2011).

79. C.-D. Tran, S. Lucas, D. G. Phillips, L. K. Randeniya, R. H. Baughman and T. T. Cong, *Nanotechnology*, **22**, 145302 (2011).

80. F. Deng, W. Lu, H. Zhao, Y. Zhu, B.-S. Kim and T.-W. Chou, *Carbon*, **49**, 1752 (2011).

81. Y. Lan, Y. Wang and Z. F. Ren, *Adv. In Phys.*, **60**, 553 (2011).

82. C. F. Cornwell and C. R. Welch. *The Journal of Chemical Phys.*, **134**, 204708 (2011).

83. M. Miao. *Carbon*, **49**, 3755 (2011).

84. L. Zhang, C. Feng, Z. Chen, L. Liu, K. Jiang, Q. Li and S. Fan, *Nano Lett.*, **8**, 2564 (2008).

85. C. Feng, K. Liu, J.-S. Wu, L. Liu, J.-S. Cheng, Y. Zhang, Y. Sun, Q. Li, S. Fan and K. Jiang, *Adv. Funct. Mater.*, **20**, 885 (2010).

86. P. Liu, L. Liu, Y. Wei, K. Liu, Z. Chen, K. Jiang, Q. Li and S. Fan,

Adv. Mater., **21**, 3563 (2009).

87. A. E. Aliev, M. D. Lima, S. Fang and R. H. Baughman, *Nano Lett.*, **10**, 2374 (2010).

88. L. Xiao, Z. Chen, C. Feng, L. Liu, Z.-Q. Bai, Y. Wang, L. Qian, Y. Zhang, Q. Li, K. Jiang and S. Fan, *Nano Lett.*, **8**, 4539 (2008).

89. L. Zhang, C. Feng, Z. Chen, L. Liu, K. Jiang, Q. Li and S. Fan, *Nano Lett.*, **8**, 2564 (2008).

90. R. Zhou, C. Meng, F. Zhu, Q. Li, C. Liu, S. Fan and K. Jiang, *Nanotechnology*, **21**, 345701 (2010).

91. H.-X. Zhang, C. Feng, Y.-C. Zhai, K.-L. Jiang, Q.-Q. Li and S.-S. Fan, *Adv. Mater.*, **21**, 2299 (2009).

92. M. Miao, J. McDonnell, L. Vuckovic and S. C. Hawkins, *Carbon*, **48**, 2802 (2010).

93. H. Zhao, Y. Zhang, P. D. Bradford, Q. Zhou, Q. Jia, F.-G. Yuan and Y. Zhu, *Nanotechnology*, **21**, 305502 (2010).

94. H.-S. Jang, S. K. Jeon and S. H. Nahm, *Carbon*, **49**, 111 (2011).

95. Y. Nakayama, *Japanese J. Appl. Phys.*, **47**, 8149 (2008).

96. G. D. Nessim, A. J. Hart, J. S. Kim, D. Acquaviva, J. Oh, C. D. Morgan, M. Seita, J. S. Leib and C. V. Thompson, *Nano Lett.*, **8**, 3587 (2008).

97. K. Jiang, J. Wang, Q. Li, L. Liu, C. Liu and S. Fan, *Adv. Mater.*, **23**, 1154 (2011).

98. M. Zhang, S. Fang, A. A. Zakhidov, S. B. Lee, A. E. Aliev, C. D. Williams, K. R. Atkinson and R. H. Baughman, *Science*, **309**, 1215 (2005).

99. W. Fu, L. Liu, K. Jiang, Q. Li and S. Fan, *Carbon*, **48**, 1876 (2010).

100. Y. Zhao, J. Wei, R. Vajtai, P. M. Ajayan and E. V. Barrera, *Scientific Reports*, **1**, 83 (2011).

101. P. Jarosz, C. Schauerman, J. Alvarenga, B. Moses, T. Mastrangelo, R. Raffaelle, R. Ridgley and B. Landi, *Nanoscale*, **3**, 4542 (2011).

102. M. Miao, S. C. Hawkins, J. Y. Cai, T. R. Gengenbach, R. Knott and C. P. Huynh, *Carbon*, **49**, 4940 (2011).

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