Supplemental information

Iodine doped carbon nanotube cables exceeding specific electrical conductivity of metals

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Table S1: The resistivity of the carbon nanotube fibers published in major articles up to date and in this work, as well as copper and aluminum.

Ref.	CNT characteristics			Comments	Electrical resistivity (Ω.m)
	Type	Length (Microns)	Diameter (nm)		
1	SWNT	<1	~1	annealed	$1*10^{-4}$
2				as-spun	$1.5*10^{-3}$
3				annealed	$7.1*10^{-3}$
4				annealed	$2*10^{-6}$
5	SWNT grown by arc discharge	-	-	as-withdraw	$3.3*10^{-6}$
6	DWNT	-	8-10	as-spun	$2*10^{-6}$
7	MWNT	100	10	twisted	$3.3*10^{-5}$
8	MWNT	650	10	un-twisted	$5.9*10^{-5}$
				twisted	$2.4*10^{-5}$
9	MWNT	-	-	twisted	$2.4*10^{-5}$
				coated with 5 wt% PVA	$1.1*10^{-5}$
This work	DWNT	>10	2-3	Raw	$5*10^{-7}$
This work	DWNT	>10	2-3	Iodine doped	$1.5*10^{-7}$
Ref.	Elements			Comments	
10	Copper			Oxygen free at 20^{o}C	$1.68*10^{-8}$
11	Aluminum			Oxygen free at 20^{o}C	$2.82*10^{-8}$

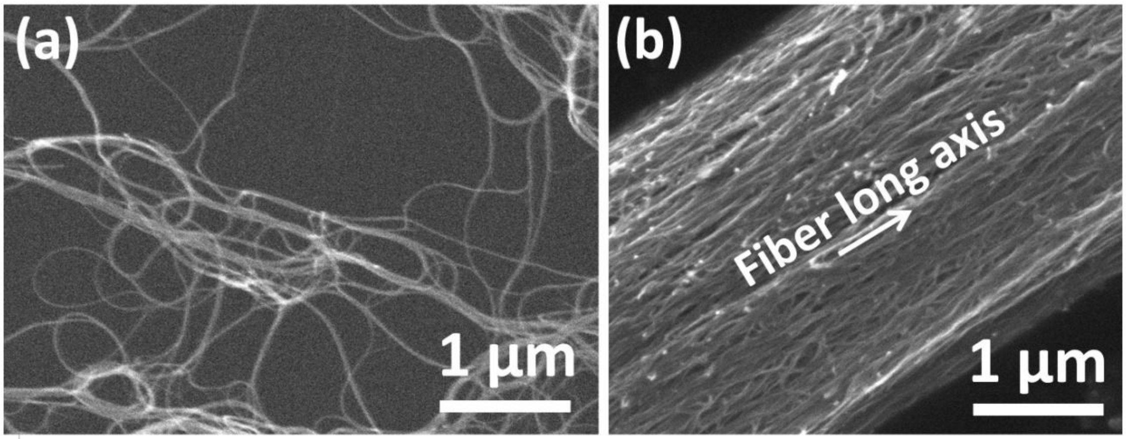

Figure S2: Morphology of the raw DWNTs and the DWNT cable. (a) SEM image of the "stocking" wall. It shows that the carbon nanotube bundles are interconnected. (b) SEM image of the raw carbon nanotube cable.

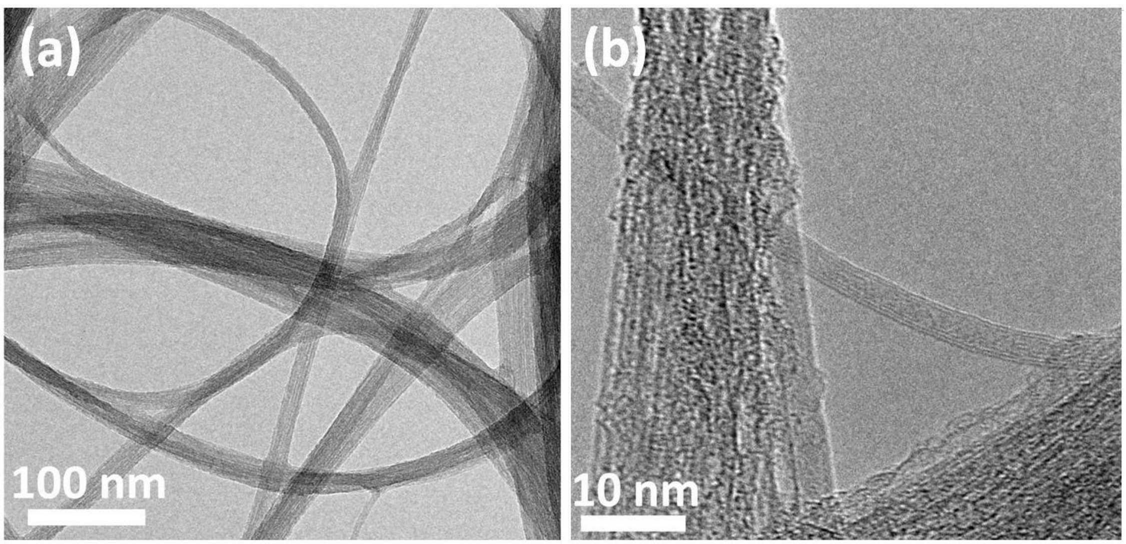

Figure S3: TEM images of the iodine doped DWNTs. (a) TEM image of the iodine doped nanotube bundles corresponding to the elemental mappings in Fig. 1. (b) TEM image of the iodine doped carbon nanotubes. The black dots wrapped around the cable appear after the iodine doping.

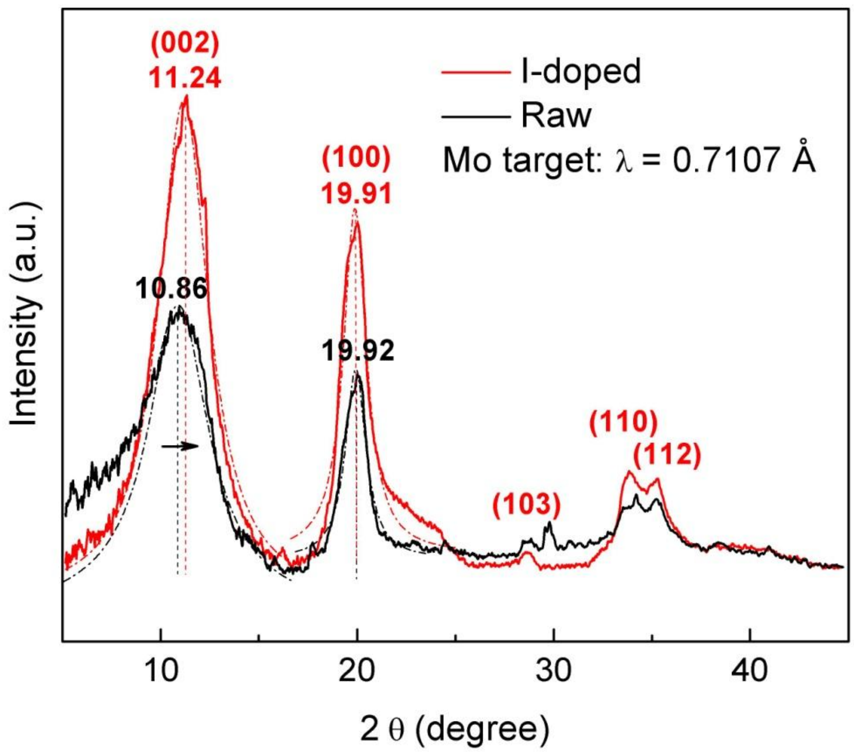

Figure S4: X-ray diffraction spectra for the raw and iodine doped cables. The (002) peak at $2\theta \sim 10.86^{o}$ corresponding to the inter-layer spacing between the outer and inner walls of the DWNTs shifts to $2\theta \sim 11.24^{o}$ after the iodine doping. The (100) peak at $2\theta \sim 19.92^{o}$ corresponding to the honeycomb lattice (The lattice spacing, d = 2.05 Å) on the nanotube wall almost does not shift. The dotted curves are the peaks generated by Gaussian fitting.

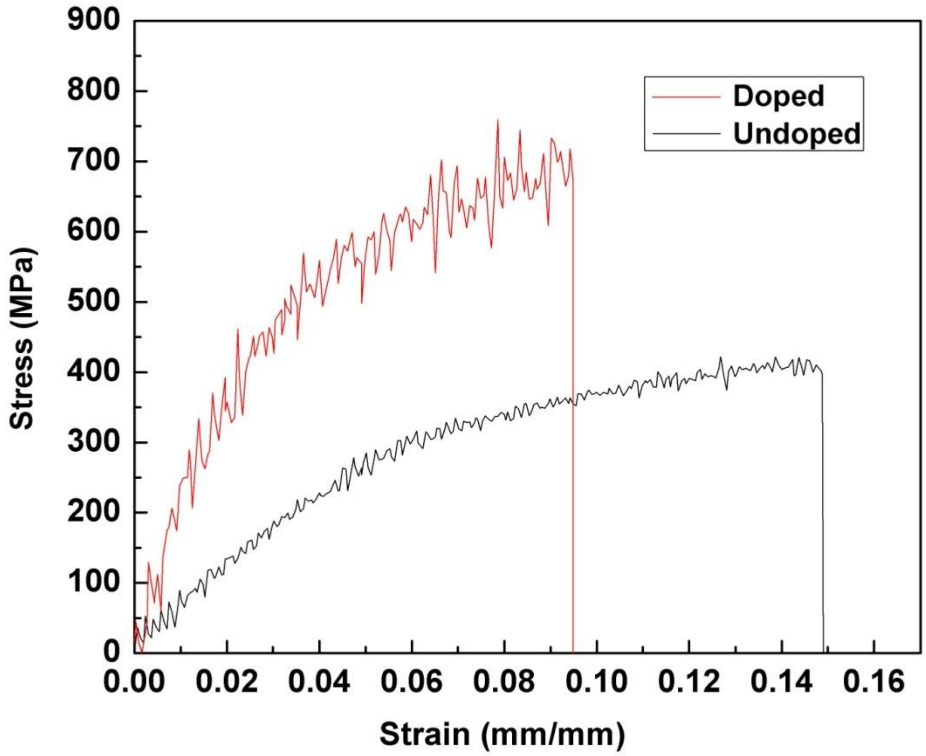

Figure S5: Stress-strain curves for the undoped and the doped fibers.

Video S6 recorded the process that the double-walled carbon nanotube (DWNT) stocking flowed out from the furnace. The Video played at 3x speed of the real time.

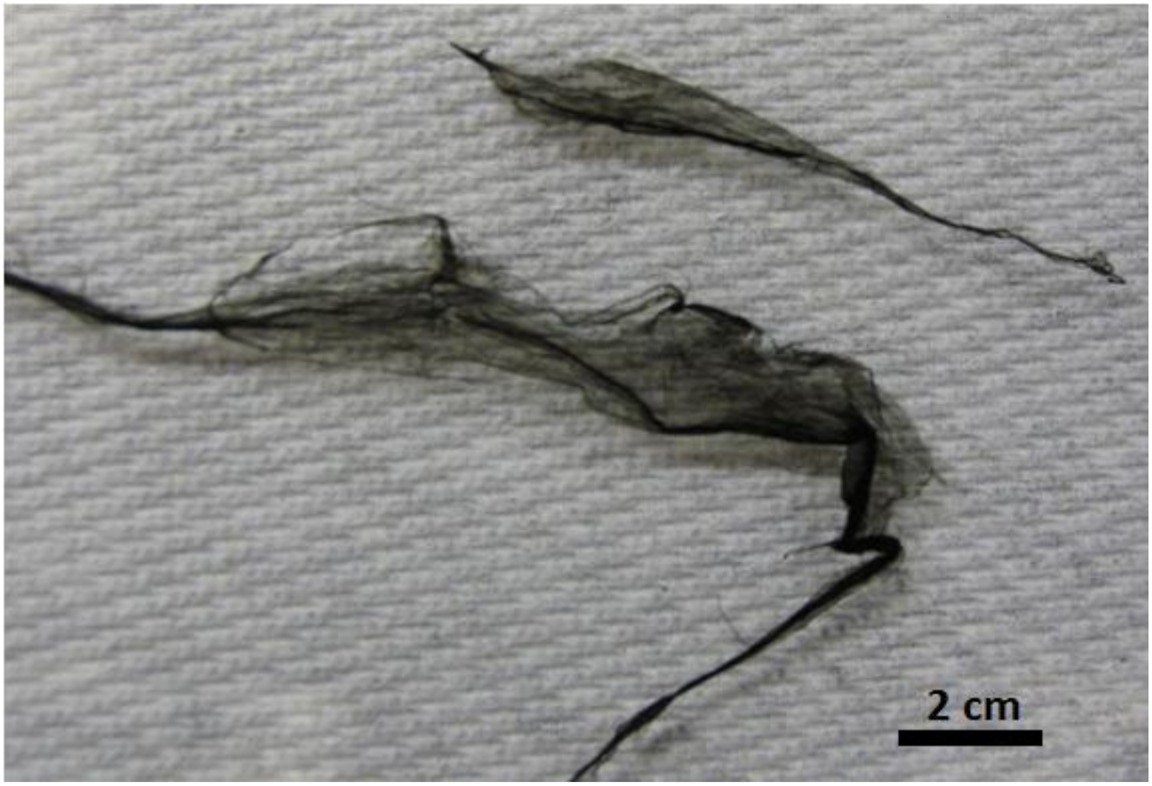

Figure S7: The DWNT bundle loosens up while soaking in 98% sulfuric acid. The picture shows two pieces of the thin film peeled off from the macroscopic bundle. The fibers of sub-10 μm diameter were produced from the even smaller ribbons, which were separated out from the thin films.

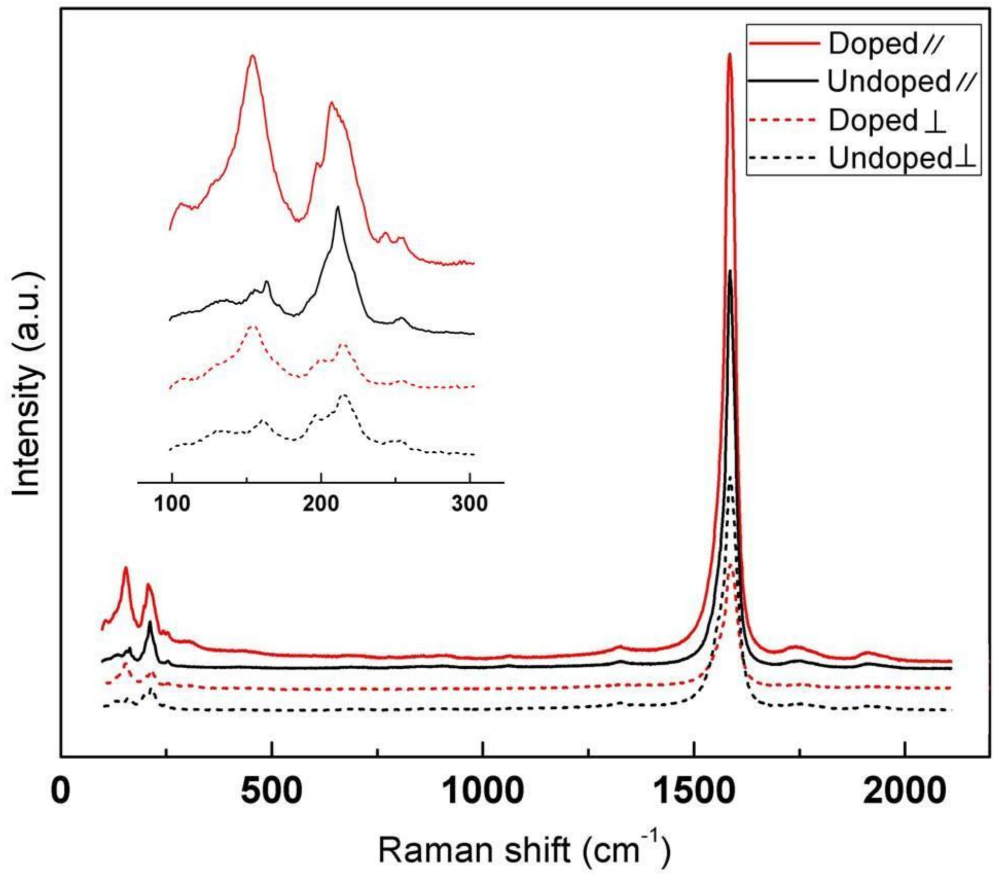

Figure S8: Raman spectra of the undoped and the doped fibers for both the parallel and the perpendicular directions to the long axis of the fibers. After doping, a peak appeared at 154 cm^{-1}. This peak may be caused by the C-I chemical bonding [12]. The fact that the peak intensity in parallel direction is larger than that in perpendicular direction indicates the DWNTs are aligned in the long axis direction of the fibers.

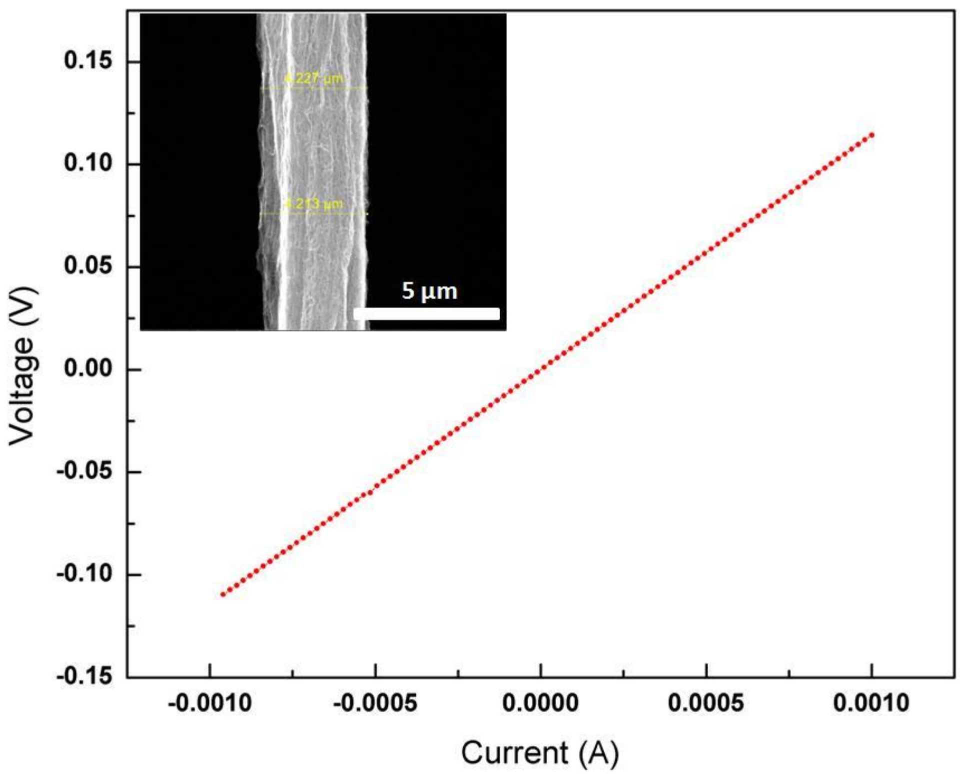

Figure S9: I-V curve for the iodine doped fiber. I-V curve is linear when the passing current is smaller than 1 mA. The linear feature is common for both the doped and the raw fibers. The slope of the I-V curve indicates the resistance of the iodine doped fiber as 114 Ω. The distance between two inner electrodes is 0.65cm. The average diameter of the iodine doped fiber is 4.22 μm as shown in the inset image. Plugging in the values of resistance, length and diameter into the formula, resistivity = $R*D^2*\pi/4/L$, the resistivity is calculated to be $2.43*10^{-5}$ Ω.cm.

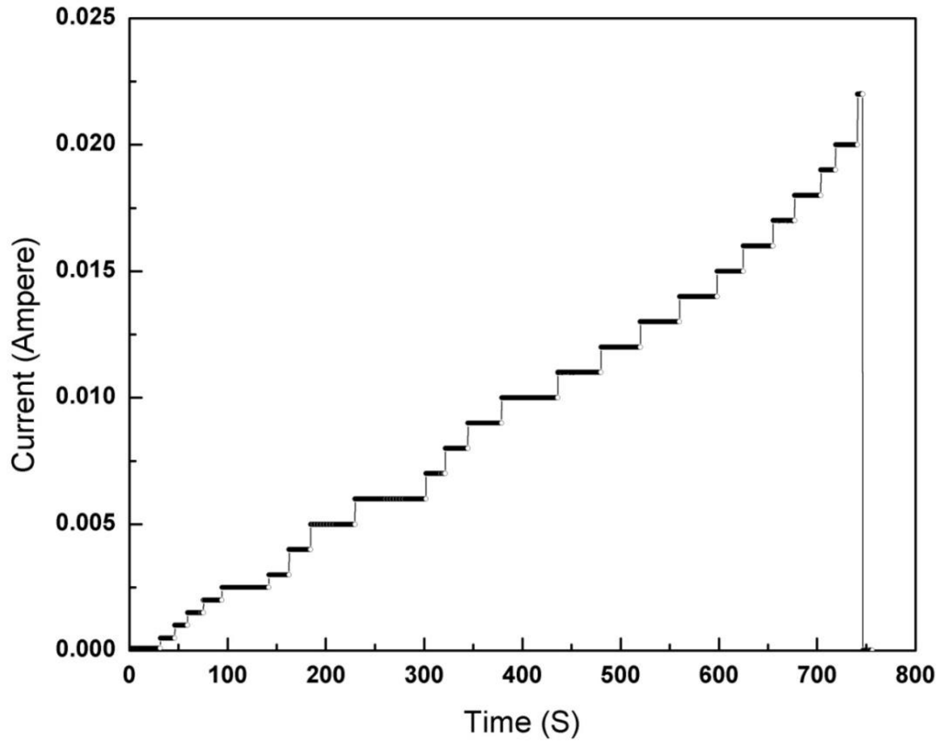

Figure S10: Curve showing current as a function of time used to determine the critical current. Critical current is the current at which the fiber breaks. The current was increased in a stepwise manner until the iodine doped fiber with a diameter of 4.2 microns broke at 22.5 mA. The current carrying capacity of this fiber is $1.62*10^5$ A/cm^2. The formula for calculating the current carrying capacity is shown as below:

$$\text{Current carrying capacity} = \frac{\text{Critical current}}{\text{Cross section}} = \frac{I}{(\pi D^2/4)}$$

W.H.Preece gave the equation for calculating the fuse current for wires in air [13], $I = A*D^{3/2}$, where A is a constant depending on the metal and D is the diameter for the wire. For copper, A = 80 (D in mm). Plug D = 4.2 microns into the formula, we get I = 21.8 mA and current carrying capacity as $1.57*10^5$ A/cm^2.

Compared to the cable as shown in figure S10, the copper wire of the same diameter has slightly smaller current carrying capacity than that of the DWNT cable.

References for Supplemental Information:

1. Badaire, S. et al. Correlation of properties with preferred orientation in coagulated and stretch-aligned single-wall carbon nanotubes. *J.Appl.Phys.* **96 (12),** 7509-7513 (2004).
2. Steinmetz, J. Glerup, M. Paillet, M. Bernier, P. Holzinger, M. Production of pure nanotube fibers using a modified wet-spinning method. *Carbon* **43,** 2397-2399 (2005).
3. Kozlov, M.E. et al. Spinning solid and hollow polymer free carbon nanotube fibers. *Adv. Mater.* **17 (5),** 614-617 (2005).
4. Ericson, L.M. et al. Macroscopic, neat, single-walled carbon nanotube fibers. *Science* **305,** 1447-1450 (2004).
5. Jang, E.Y. et al. Macroscopic single-walled-carbon-nanotube fiber self-assembled by dip-coating method. *Adv. Mater.* **21,** 4357-4361 (2009).
6. Zhong, X.H. et al. Continuous multilayered carbon nanotube yarns. *Adv. Mater.* **22,** 692-696 (2010).
7. Zhang, M. Atkinson, K.R. Baughman, R.H. Multifunctional carbon nanotube yarns by downsizing an ancient technology. *Science* **306,** 1358-1361 (2004).
8. Zhang, X.F. et al. Strong carbon-nanotube fibers spun from long carbon-nanotube arrays. *Small* **3 (2),** 244-248 (2007).
9. Liu, K. et al. Scratch-resistant, highly conductive, and high-strength carbon nanotube based composite yarns. *ACS nano* **4 (10),** 5827-5834 (2010).
10. http://en.wikipedia.org/wiki/Copper
11. http://en.wikipedia.org/wiki/Aluminum
12. Cambedouzou, J. et al. Raman spectroscopy of iodine-doped double-walled carbon nanotubes. *Phys. Rev. B* **69,** 235422 (2004).
13. Preece, W.H. *Royal Soc. Proc.* **36**, 464, (1884).