Supplementary Information

Carbon Nanotubes: How Strong is Their Bond with the Substrate?

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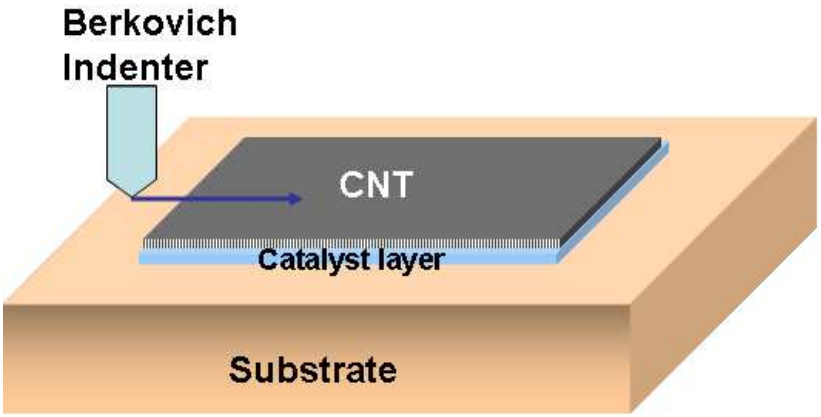
Supporting Information Table S1: Overview of literature reported CNT-substrate adhesion testing methods

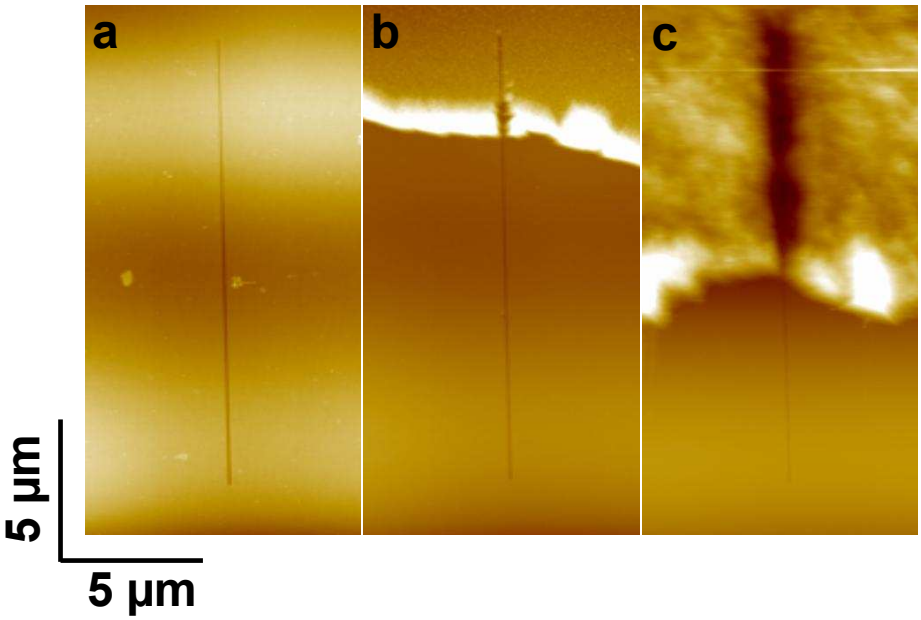
Techniques	Adhesion strength or energy	Remarks	Reference
Blowing, rubbing, brushing	NA	Qualitative method, unreliable technique, extremely user sensitive	1
Ultrasonication in solvent	NA	Qualitative method, widely used for understanding bond of CNTs with substrates, results may vary in different laboratories	2-6
Dropping, shaking, bending samples several times	NA	Qualitative method, unreliable technique, extremely user sensitive	7
Peel test using adhesive tape	NA	Qualitative method, widely used for understanding bond of CNTs with substrates, highly operator sensitive	7-9
Pulling CNTs by tweezers	NA	Qualitative method, result may vary for different operators or tweezers	10
Hanging known	0.12-0.18 MPa	Used for quantifying strength of	11, 12

weights from substrate		CNT based adhesive tapes: able to quantify adhesion of CNTs with substrate but not calibrated against standards, only a range of de-bonding stress could be predicted in absence of continuous load-displacement plot, stress can not be predicted as contact area is not known, accurate breaking/de-bonding position (whether at CNT-substrate interface or along the length of CNT itself) is not known can not predict bond strength/energy for single CNTs	
Tensile test after wrapping the CNTs by adhesive tape	0.26-0.50 MPa	Used for quantifying bonding of CNTs grown on wire substrates: not calibrated against standards, stress can not be predicted as contact area is not known, accurate breaking/de-bonding	13, 14

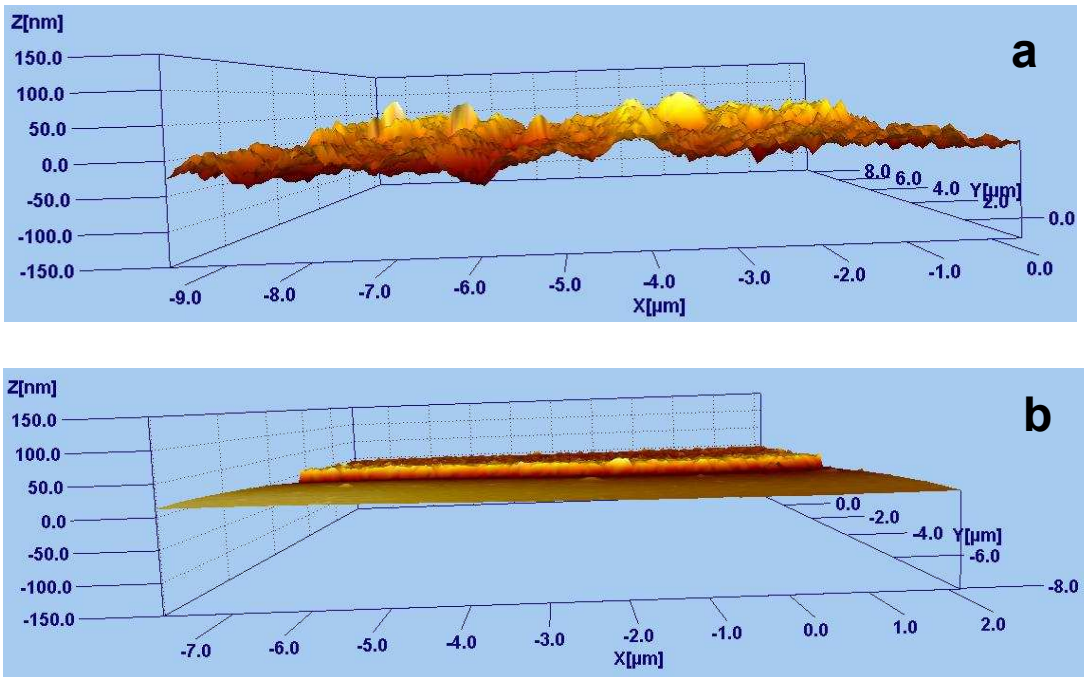
		position not known can not predict bond strength/energy for single CNTs	
Compression test using Cu tape to contact CNTs	2.05 MPa	Used for quantifying bonding of CNTs grown on flat substrates: not calibrated against standards, stress can not be predicted as contact area is not known, accurate breaking/de-bonding position not known can not predict bond strength/energy for single CNTs	15



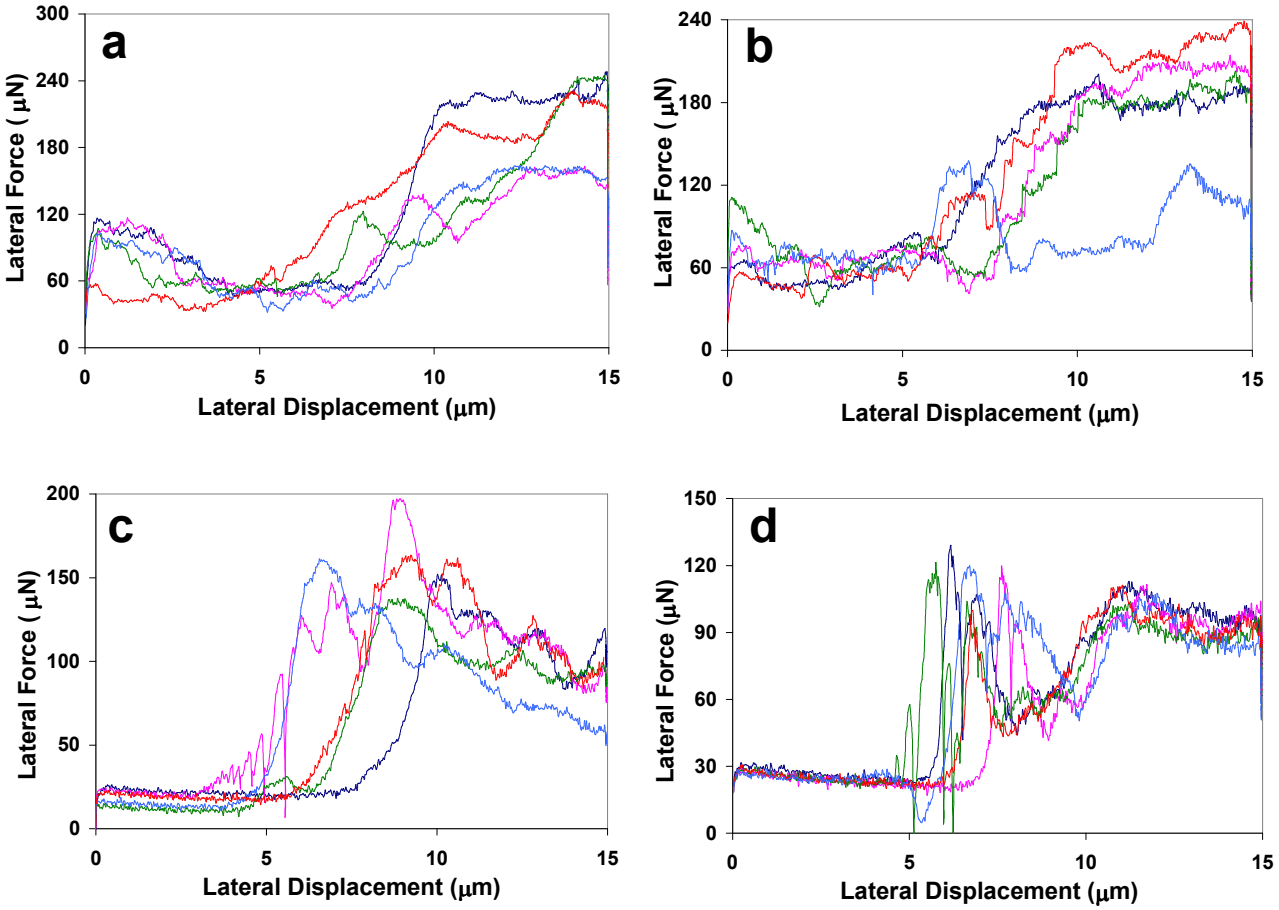
Supporting Information Figure S1: Schematic of the nano-scratch method, followed in the present study. A normal load of 150 μN was used for all the scratch tests.



Supporting Information Figure S2: 2-dimensional scanning probe microscopy (SPM) images of the nano-scratches, made on samples with Si-substrate. From left to right, (a) scratches are visible on bare sample, (b) only catalyst deposited sample and (c) sample after CNT growth.



Supporting Information Figure S3: Scanning probe microscopy (SPM) images of the (a) Cu and (b) Si substrates after catalyst deposition.



Supporting Information Figure S4: Nano-scratch tests on Cu (a and b) and Si (c and d) substrates, after a CNT growth time of 2 minutes (a and c) and 30 minutes (b and d). Both the samples have shown approximately same lateral force increment values for 2 minutes and 30 minutes, indicating that length of CNTs (which is much higher for 30 minutes samples) do not affect the scratching force to any significant level.

References of Supporting Information

1. Bower, C.A.; Zhou, O.; Zhu, W. Method for Fabrication of Patterned CNT Films (US Patent # US 627318 B1, Aug 21, 2001).

2. Chen, Z.; Zhang, Q.; Lan, P.; Zhu, B.; Yu, T.; Cao, G.; den Engelsen, D. Ultrahigh-Current Field Emission from Sandwich-Grown Well-Aligned Uniform Multi-Walled Carbon Nanotube Arrays with High Adherence Strength. *Nanotechnology* 2007, 18, 265702.

3. Choi, C.Y.; Zheng, Z.; Wong, K.W.; Du, Z.L.; Lau, W.M.; Du, R.X. Fabrication of Cross-Linked Multi-Walled Carbon Nanotube Coatings with Improved Adhesion and Intrinsic Strength by a Two-Step Synthesis: Electrochemical Deposition and Hyperthermal Proton Bombardment. *Appl. Phys. A* 2008, 91, 403-406.

4. Qin, Y. ; Hu, M. Field Emission Properties of Electrophoretic Deposition Carbon Nanotubes Film. *Appl. Surf. Sci.* 2009, 255, 7618-7622.

5. Su, H.-C.; Chen, C.-H.; Chen, Y.-C.; Yao, D.-J.; Chen, H.; Chang, Y.-C.; Ywe, T.-R. Improving the Adhesion of Carbon Nanotubes to a Substrate Using Microwave Treatment. *Carbon* 2010, 48, 805-812.

6. Jeong, T.; Heo, J.; Lee, J.; Lee, S.; Kim, W.; Lee, H.; Park, S.; Kim, J.M.; Oh, T.; Park, C. *et al.* Improvement of Field Emission Characteristics of Carbon Nanotubes through Metal Layer Intermediation. *Appl. Phys. Lett.* 2005, 87, 063112.

7. Thomas, B.J.C.; Boccaccini, A.R.; Shaffer, M.S.P. Multi-Walled Carbon Nanotube Coatings Using Electrophoretic Deposition. *J. Am. Cer. Soc.* 2005, 88, 980-982.

8. Cho, J.; Schaab, S.; Roether, J.A.; Boccaccini, A.R. Nanostructured Carbon Nanotube/TiO_2 Composite Coatings using Electrophoretic Deposition (EPD). *J. Nanopart. Res.* 2008, 10, 99-105.

9. Radhakrishnan, J.K.; Pandian, P.S.; Padaki, V.C.; Bhusan, H.; Rao, K.U.B.; Xie, J.; Abraham, J.K.; Varadan, V.K. Growth of Multiwalled Carbon Nanotube Arrays by Chemical Vapour Deposition over Iron Catalyst and the Effect of Growth Parameters. *Appl. Surf. Sci.* 2009, 255, 6325-6334.

10. Zhu, L.; Hess, D.W.; Wong, C.P. Assembly of Fine-Pitch Carbon Nanotube Bundles for Electrical Interconnect Applications. *Mater. Res. Soc. Symp. Proc.* 2007, 990, 0990-B10-01.

11. Zhao, Y.; Tong, T.; Delzeit, L. Interfacial Energy and Strength of Multiwalled-Carbon-Nanotube-based Dry Adhesive. *J. Vac. Sci. Technol. B* 2006, 24, 331-335.

12. Qu, L.; Dai, L.; Stone, M.; Xia, Z.; Wang, Z.L. Carbon Nanotube Arrays with Strong Shear Binding-On and Easy Normal Lifting-Off. *Science* 2008, 322, 238-42.

13. Cao, A.; Veedu, V.P.; Li, X.; Yao, Z.; Ghasemi-Nejhad, M.N.; Ajayan, P.M. Multifunctional Brushes Made from Carbon Nanotubes. *Nature Mater.* 2005, 4, 540-545.

14. Talapatra, S.; Kar, S.; Pal, S.K.; Vajtai, R.; Ci, L.; Vicor, P.; Shaijumon, M.M.; Kaur, S.; Nalamasu, O.; Ajayan, P.M. Direct Growth of Aligned Carbon Nanotubes on Bulk Metals. *Nature Nanotech.* 2006, 1, 112-116.

15. Zhang, Y.; Suhir, E.; Xu, Y.; Gu, C. Bonding Strength of a Carbon Nanofiber Array to its Substrate. *J. Mater. Res.* 2006, 21, 2922-2926.