Novel electrical switching behaviour and logic in carbon nanotube Y-junctions

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Carbon-nanotube-based electronics offers significant potential as a nanoscale alternative to silicon-based devices for molecular electronics technologies. Here, we show evidence for a dramatic electrical switching behaviour in a Y-junction carbon-nanotube[1–3] morphology. We observe an abrupt modulation of the current from an on- to an off-state, presumably mediated by defects and the topology of the junction. The mutual interaction of the electron currents[4] in the three branches of the Y-junction is shown to be the basis for a potentially new logic device. This is the first time that such switching and logic functionalities have been experimentally demonstrated in Y-junction nanotubes without the need for an external gate. A class of nanoelectronic architecture and functionality, which extends well beyond conventional field-effect transistor technologies[5,6], is now possible.

So far, the elucidation of fundamental properties of nanotubes and nanowires[7–10] and their applicability for electrical devices has mainly focused on adopting the metal-oxide-semiconductor field-effect transistor paradigm[11–13], where a nanotube serves as the channel between lithographically fabricated electrodes (namely, source and drain), and an electrically insulated gate modulates the channel conductance. In other demonstrations, cumbersome atomic force microscope manipulations[14] of nanotube properties have been used. To realize a truly nanoelectronic architecture, it is desirable to have a fully integrated nanotube-based technology, where both devices and interconnects are based on carbon nanotubes (CNTs). Further, it would be attractive in proposing new nanoelectronic elements to harness new functionalities peculiar to novel CNT forms, such as Y-junctions. Here, we focus on the electrical measurements on a particular multiwalled CNT (MWNT) morphology—the Y-junction—which is grown by a modified chemical vapour deposition (CVD) process[15]. We have observed unique switching behaviour and the promise of using this element as a new type of logic device.

It was derived theoretically[4] and proved experimentally[16] in lithographically patterned two-dimensional electron gases that the ballistic nature of the electron transport and electron–electron interactions in Y-shaped nanostructures result in nonlinear current (I)–voltage (V) characteristics and novel device paradigms[5,17]. Current modulation in these structures involves new principles of electron momentum engineering in contrast to the well-known band engineering. An advantage of this approach, over a conventional field-effect transistor, is that the current is only switched between two outputs rather than completely turned on/off[18,19], which leads to higher speed and efficiency of operation. Y-junction nanotubes provide a more natural and truly nanoscale alternative avenue to explore this switching behaviour. Branching in nanotubes necessitates the presence of topological defects, to satisfy the local bond order, at the junction region for maintaining a low-energy configuration for the carbon atoms[20]. Further, there is the inevitable presence of metal catalyst particles introduced at the junction during synthesis[15]. The delocalization of the electrons over these defects leads to a net charge that acts as a localized scattering centre for modulating the electron-transport characteristics. The consequent gating action from the junction could be responsible for a variety of nonlinear behaviours, which could be exploited for novel applications[5,17,21] including (a) switching and transistor action, (b) logic gates and (c) higher harmonic-frequency generation.

Although existing theoretical work is mostly focused on single-walled nanotubes, similar principles[22], namely (i) the formation of an asymmetric scattering centre/quantum dot[18] at the junction (Fig. 1a), (ii) finite length of the stem and branches connected to metallic leads, (iii) asymmetry of the bias applied/the potential profile[23] across the nanotube and (iv) the Schottky barrier at the nanotube-contact metal leads[24], would again be important in completely determining the electrical characteristics of the Y-junction devices.

The CNT Y-junctions (Fig. 1b) were grown on bare quartz or SiO_2/Si substrates through thermal CVD using a carbon feedstock mixture of ferrocene and xylene together with Ti containing precursor gases. The branching, for Y-junction formation, can be introduced at will through the introduction of the Ti precursor. For further details on the growth mechanism and processes, see ref. 15.

The samples for electrical measurements were prepared by suspending the nanotube Y-junctions in ethanol and depositing them on a SiO_2/Si substrate with patterned Au pads (Fig. 1c). Y-junctions, in proximity to the Au contact pads, were then located using a scanning electron microscope (SEM, model FEI Strata

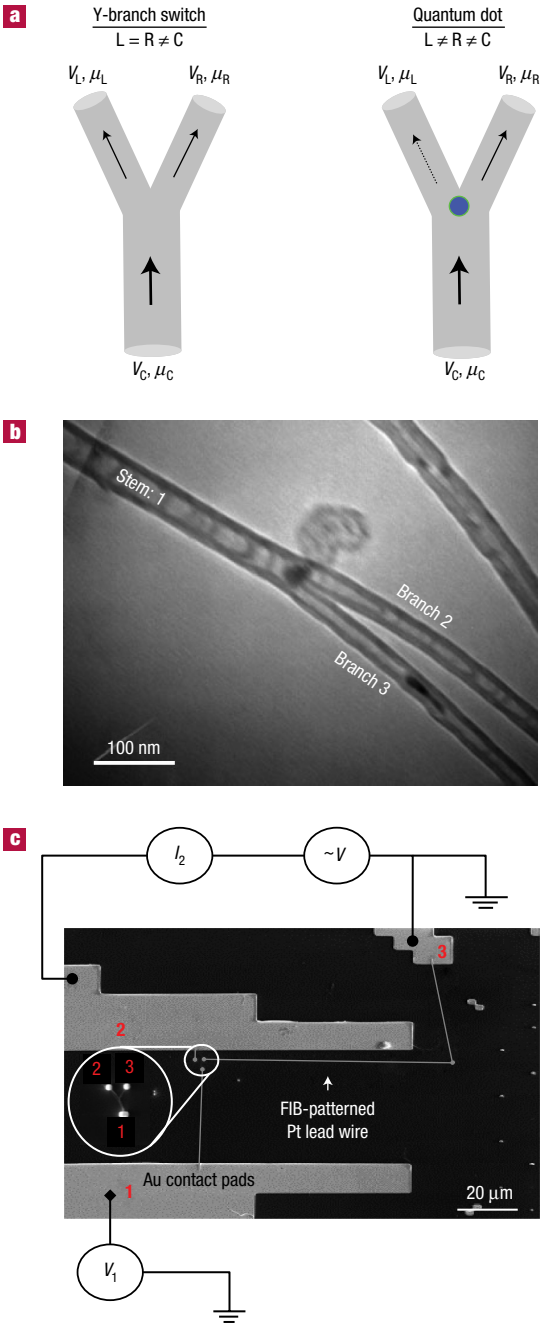

Figure 1 The CNT Y-junction morphology and experimental arrangement for measuring transport properties. a, The Y-junction can be used as a prototypical nanoelectronic element for a variety of functions such as switching or as a quantum dot, depending on the transmission characteristics of the constituent branches. L, R and C refer to the left, right and central/stem branches of a Y-junction. **b**, A transmission electron microscope (JEOL 3010) image of a typical MWNT Y-junction used in the present measurements. The Fe–Ti catalyst particles formed in the CVD growth along with the presence of topological defects at the junction region can influence the electrical transport characteristics. **c**, An SEM micrograph of the overall circuit arrangement used in the measurement of the electrical characteristics, with Au contact pads and an FIB-patterned Pt wire contacting the Au pads and the Y-junction. A configuration is shown where a control d.c. voltage is applied on the stem (terminal 1) of the Y-junction, and the current flow through the other two branches in response to a constant a.c. bias voltage ($\sim V$) is monitored. Similarly, control voltages can be applied on branches 2 and 3 for characterizing the Y-junction in detail.

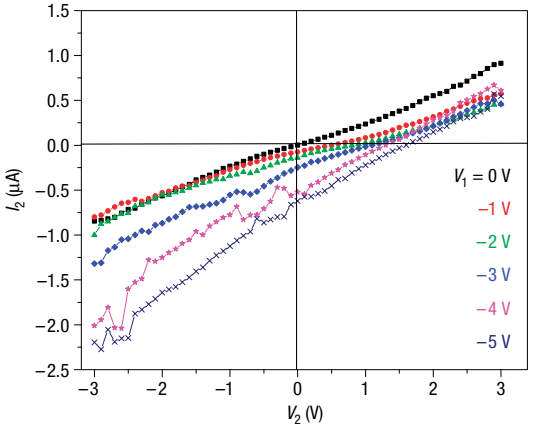

Figure 2 Current (I)–voltage (V) characteristics of a Y-junction. A constant d.c. voltage is applied on the stem (1 in Fig. 1b), while the current in branch 2 is monitored as a function of applied voltage (from top to bottom: 0 V; −1 V; −2 V; −3 V; −4 V; −5 V). The gating action of the voltage and the asymmetric response[29] should be noted.

235 M dual beam) equipped with a focused ion beam (FIB). The sample was scanned at 5 kV to locate the Y-junctions, which results in minimal damage[25,26] to the nanotubes. The ion-beam in the FIB-SEM was then used to deposit the Pt lead wires that connect the terminals of the Y-junction to the contact pads (Fig. 1c inset)[27]. Special care[26] was taken to not expose the nanotubes to the ion-beam to prevent radiation damage. A Wentworth probe station, with needle contacts[24], was used to apply the voltages and measure currents.

The electrical transport properties of the Y-junctions were probed through both two- and three-terminal phase-sensitive lock-in amplifier measurements in air, at room temperature, in the dark. There was little difference in the $I-V$ characteristics between air and vacuum, and a negligible transient response to white light illumination[8]. The resistances measured in d.c. were checked to be in accordance with the lock-in measurements. By successively grounding each branch of the Y-junction, we were able to probe the intra-branch (that is, 1, 2 and 3) and inter-branch (that is, 1–2, 1–3 and 2–3) resistances. If it is assumed that the ohmic contact resistance for all three branches of the Y-junction is identical, this measurement can identify the individual branch's transport characteristics. (It was not possible to determine all four parameters R_1, R_2, R_3 and the contact resistance with three-terminal measurements.) We tested around five samples and obtained reproducible results. When measured pair-wise (that is, 1–2, 1–3 and 2–3) we observe ohmic behaviour, with resistances in the range of 100−400 kΩ. Although MWNTs are expected to have a resistance smaller than around 13 kΩ ($h/2e^2$; where h is the Planck constant and e the electron charge) ideal ohmic contacts through metal evaporation were difficult to achieve. However, reproducible $I-V$ characteristics on a large number of samples would imply that the observed behaviour is intrinsic to the Y-junctions. High-temperature thermal annealing was successful in reducing the contact resistance by an order of magnitude, with similar switching behaviour, and is a possible solution to achieving low-resistance contacts in the future. However, local electron exposure[28] onto the CNT-ohmic contact did not affect the contact resistance significantly.

The gating action of the stem (1 in Fig. 1b) on the $I-V$ characteristics of the branches in the Y-junction (2 and 3 in Fig. 1b) is illustrated in Fig. 2. The asymmetric behaviour,

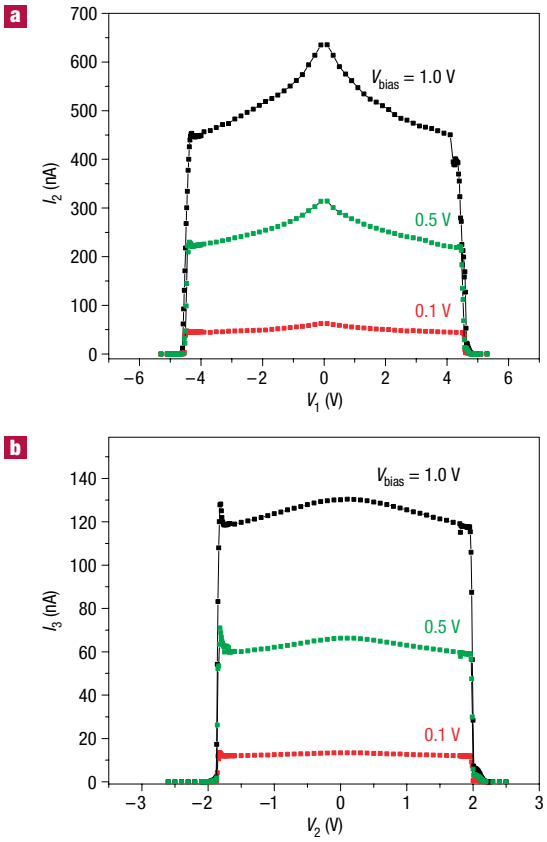

Figure 3 Observation of near-perfect electrical switching in Y-junctions. An abrupt modulation of the electrical current through two branches of the Y-junction is seen on varying the d.c. bias voltage on the third branch. **a**, The voltage at which the switching action occurs is ~4.6 V on the stem. **b**, The switching on both of the branches occurs at ~2 V. The disparate voltage values could be related to the character, diameter, defects and so on, of the constituents (branch/stem) of the Y-junction.

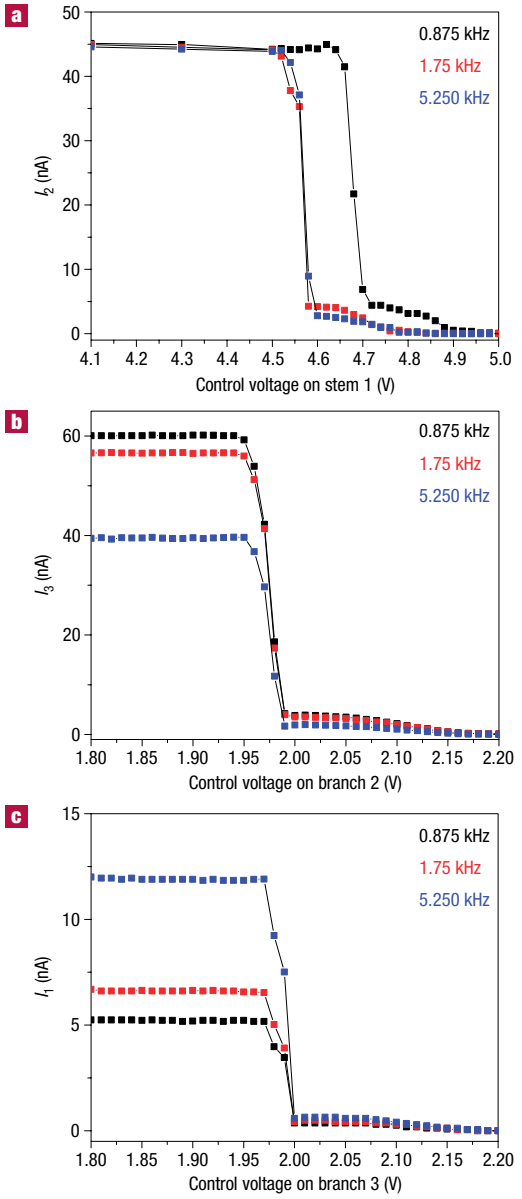

Figure 4 Frequency response of the switching characteristic in the Y-junction. In **a**, the control voltage is applied on the stem (1) of the Y-junction while the current, under an a.c. bias, is monitored across the other two terminals of the Y-junction. In **b** and **c**, a control d.c. voltage is applied on branches 2 and 3. The magnitudes of the current differ owing to the different resistances of the Y-junction constituents.

where $I(+V) \neq I(-V)$, had been theoretically predicted earlier[29] and this is the first time that the effect of a gate voltage has been experimentally demonstrated. On the basis of these results, we explored the possibility of using the CNT Y-junctions for switching applications, as an electrical inverter, analogous to earlier[16,19] Y-branch switch studies in lithographically patterned two-dimensional electron gases. In our measurements, a control d.c. voltage was swept on one terminal of the Y-junction and the current through the other two terminals probed under a fixed a.c. bias ranging from 0.1 to 1.0 V. As the d.c. voltage is increased, at a certain point the Y-junction goes from nominally conducting to a pinched-off state (Fig. 3). This switching behaviour was observed for all three terminals of the Y-junction, at varying d.c. bias voltages, in different samples. For example, the channel is pinched-off when ~4.6 V is applied to the stem (Fig. 3a), to lower than the ~2 V (Fig. 3b) needed to observe the pinch-off when the control voltage is applied to the branches (2 and 3). The switching behaviour was seen over a wide range of frequencies (Fig. 4), with an upper limit of around 57 kHz being set by the capacitive response of the Y-junction, when the current tends to zero. The transconductance (dI/dV_{gate}) of the Y-junction devices is around 10^{-6} A V^{-1}, which compares well to a single-walled CNT channel transistor (10^{-8} A V^{-1}) (ref. 12).

As the bias voltage applied to our MWNT Y-junction is substantial, it is expected that many walls of the MWNT would contribute[10] to the electronic conduction. The presence of catalyst nanoparticles (see Fig. 1b) in the conduction paths would blockade current flow, and their charging could account for the abrupt drop-off of the current. The exact magnitude of the switching voltage would then be related to the exact size of the nanoparticle. This suggests the possibility of nano-engineering the Y-junction to get a variety of switching behaviours. An alternative possibility is that there is inter-mixing of the currents in the Y-junction, where the electron transmission is abruptly cut off owing to the compensation of currents, for example, the current through branches 2 and 3 is cancelled by current leakage through stem 1.

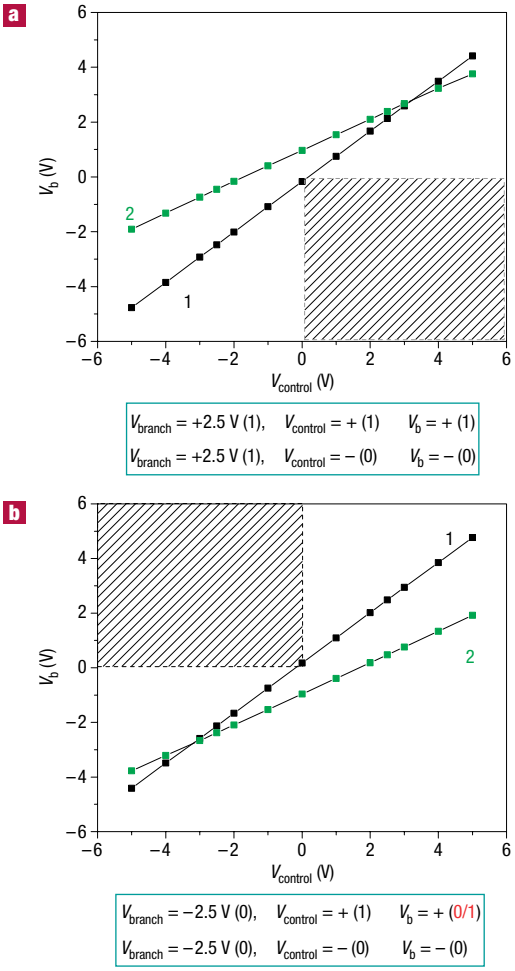

Figure 5 The CNT Y-junction for logic applications. The continuity of the electrochemical potential from one branch of the CNT Y-junction to another (see the text) could be used for the basis for a prototypical logic device. A constant voltage (positive in **a** and negative in **b**) is applied on one branch (V_{branch}), and the voltage monitored across the second branch (V_b), while a control d.c. voltage ($V_{control}$) is swept across the third branch of the Y-junction. The two lines (green and black) refer to the possible permutations of the voltages applied on the two branches (2 and 3 in Fig. 1b). The inter-mixing of the currents between the three branches could be responsible for the partial realization of an AND gate.

Further research is needed to clarify the exact mechanisms in these interesting phenomena.

When finite voltages are applied to the left and the right branches of a Y-junction, in a push–pull fashion (that is, $V_{left} = -V_{right}$ or *vice versa*), the voltage output at the stem would have the same sign as the terminal with the lower voltage[4]. This dependence follows from the principle of continuity of electrochemical potential ($\mu = -eV$) in electron transport through a Y-junction and forms the basis for the realization of an AND[5] logic gate, that is, when either of the branch voltages is negative (say, corresponding to a logic state of 0), the voltage at the stem is negative and positive voltage (logic state of 1) at the stem is obtained only when both the branches are at positive biases. We report the results of our measurements in Fig. 5, where a constant voltage (positive/negative) is imposed on one branch, while the voltage across the other branch ($V_{control}$) is swept from −5 to +5 V, and the output voltage from the third branch (V_b) is monitored. In a naturally formed CNT-based Y-junction, as is the case here, the distinction between stem and branch is not very clear. The deviation from the realization of a perfect AND gate could then be due to inter-mixing between the conduction channels and the currents from the three branches of the Y-junction.

We wish to emphasize that this is the first time that such an abrupt electrical switching behaviour has been seen in CNT Y-junctions. Before this work, only diode-like behaviour[3,30] has been observed. Through this work, we are enabling and adding a new functionality to nanotube electronics, that is, switching, making an overall CNT-based nanoelectronic architecture more complete and feasible. The detailed nature of the abrupt electrical switching behaviour is not completely understood but can be a fertile ground for future research, for example, in defect engineering where one can intentionally modify, mechanically or chemically, the paths of electronic conduction in the Y-junction.

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References

1. Zhou, D. & Seraphin, S. Complex branching phenomena in the growth of carbon nanotubes. *Chem. Phys. Lett.* **238,** 286–289 (1995).
2. Li, W. Z., Wen, J. G. & Ren, Z. F. Straight carbon nanotube Y junctions. *Appl. Phys. Lett.* **79,** 1879–1881 (2001).
3. Satishkumar, B. C., Thomas, P. J., Govindaraj, A. & Rao, C. N. R. Y-junction carbon nanotubes. *Appl. Phys. Lett.* **77,** 2530–2532 (2000).
4. Xu, H. Q. Electrical properties of three-terminal ballistic junctions. *Appl. Phys. Lett.* **78,** 2064–2066 (2001).
5. Xu, H. Q. *et al.* Novel nanoelectronic triodes and logic devices with TBJs. *IEEE Electron Dev. Lett.* **25,** 164–166 (2004).
6. Baughman, R. H., Zakhidov, A. A. & de Heer, W. A. Carbon nanotubes-the route toward applications. *Science* **297,** 787–792 (2002).
7. Saito, R., Dresselhaus, G. & Dresselhaus, M. S. *Physical Properties of Carbon Nanotubes* (Imperial College Press, London, 1998).
8. Forro, L. & Schonenberger, C. in *Carbon Nanotubes-Topics in Applied Physics* (ed. Avouris, P.) (Springer, Heidelberg, 2001).
9. Kim, P., Shi, L., Majumdar, A. & McEuen, P. L. Thermal transport measurements of individual multiwalled nanotubes. *Phys. Rev. Lett.* **87,** 215502 (2001).
10. Collins, P. G., Hersam, M., Arnold, M., Martel, R. & Avouris, P. Current saturation and electrical breakdown in mutiwalled carbon nanotubes. *Phys. Rev. Lett.* **86,** 3128–3131 (2001).
11. Martel, R., Schmidt, T., Shea, H. R., Hertel, T. & Avouris, P. Single- and multi-wall carbon nanotube field-effect transistors. *Appl. Phys. Lett.* **73,** 2447–2449 (1998).
12. Tans, S. J., Verschueren, A. R. M. & Dekker, C. Room-temperature transistor based on a single carbon nanotube. *Nature* **393,** 49–52 (1998).
13. Javey, A., Guo, J., Wang, Q., Lundstrom, M. & Dai, H. Ballistic carbon nanotube field-effect transistors. *Nature* **424,** 654–657 (2003).
14. Postma, H. W. C., Teepen, T., Yao, Z., Grifoni, M. & Dekker, C. Carbon nanotube single-electron transistors at room temperature. *Science* **293,** 76–79 (2001).
15. Gothard, N. *et al.* Controlled growth of Y-junction nanotubes using Ti-doped vapor catalyst. *Nano Lett.* **4,** 213–217 (2004).
16. Shorubalko, I., Xu, H. Q., Omling, P. & Samuelson, L. Tunable nonlinear current-voltage characteristics of three-terminal ballistic nanojunctions. *Appl. Phys. Lett.* **83,** 2369–2371 (2003).
17. Shorubalko, I. *et al.* A novel frequency-multiplication device based on three-terminal ballistic junction. *IEEE Electron Dev. Lett.* **23,** 377–379 (2002).
18. Song, A. M. *et al.* Nonlinear electron transport in an asymmetric microjunction: A ballistic rectifier. *Phys. Rev. Lett.* **80,** 3831–3834 (1998).
19. Palm, T. & Thylen, L. Designing logic functions using an electron waveguide Y-branch switch. *J. Appl. Phys.* **79,** 8076–8081 (1996).
20. Andriotis, A. N., Menon, M., Srivastava, D. & Chernozatonski, L. Transport properties of single-wall carbon nanotube Y-junctions. *Phys. Rev. B* **65,** 165416 (2002).
21. Csontos, D. & Xu, H. Q. Quantum effects in the transport properties of nanoelectronic three-terminal Y-junction devices. *Phys. Rev. B* **67,** 235322 (2003).
22. Andriotis, A. N., Srivastava, D. & Menon, M. Comment on "Intrinsic electron transport properties of carbon nanotube Y-junctions". *Appl. Phys. Lett.* **83,** 1674–1675 (2003).
23. Tian, W. *et al.* Conductance spectra of molecular wires. *J. Chem. Phys.* **109,** 2874–2882 (1998).
24. Heinze, S. *et al.* Carbon nanotubes as Schottky barrier transistors. *Phys. Rev. Lett.* **89,** 106801 (2002).
25. Crespi, V. H., Chopra, N. G., Cohen, M. L., Zettl, A. & Louie, S. G. Anisotropic electron-beam damage and the collapse of carbon nanotubes. *Phys. Rev. B* **54,** 5927–5931 (1996).
26. Banhart, F. Irradiation effects in carbon nanostructures. *Rep. Prog. Phys.* **62,** 1181–1221 (1999).
27. Gopal, V. *et al.* Rapid prototyping of site-specific nanocontacts by electron and ion beam assisted direct-write nanolithography. *Nano Lett.* **4,** 2059–2063 (2004).
28. Bachtold, A. *et al.* Contacting carbon nanotubes selectively with low-ohmic contacts for four-probe electric measurements. *Appl. Phys. Lett.* **73,** 274–276 (1998).
29. Andriotis, A. N., Menon, M., Srivastava, D. & Chernozatonski, L. Rectification properties of carbon nanotube "Y-junctions". *Phys. Rev. Lett.* **87,** 066802 (2001).
30. Papadapoulos, C., Rakitin, A., Li, J., Vedeneev, A. S. & Xu, J. M. Electronic transport in Y-junction carbon nanotubes. *Phys. Rev. Lett.* **85,** 3476–3479 (2000).

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Competing financial interests

The authors declare that they have no competing financial interests.