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Electrical characterization of carbon nanotube Y-junctions: a foundation for new nanoelectronics

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Abstract A review on the syntheses and electrical characterization of Y-shaped multi-walled carbon nanotube morphologies is presented. Modified thermal CVD processes, using Ti precursors, are used to grow Y-junctions of different geometries and distribution of catalyst particles. It has been established that novel electrical switching behavior is feasible, where any one of the three branches of the Y-junction can be used for modulating the electrical current flow through the other two branches. Current blocking behavior, leading to perfect rectification, is seen which could be related to the interplay of the carrier lifetime and the transit time. The overall goal is to investigate the possibility of obtaining novel functionality at the nanoscale, which can lead to new device paradigms.

Introduction

Carbon based nano-electronics technology [1] promises greater flexibility compared to conventional silicon electronics, one example being the extraordinarily large variety of carbon based organic structures. In recent years, carbon nanotubes (CNT) have emerged as one of the foremost manifestations of this technology and extensive research has been expended in probing their electronic properties. In the current paper, we examine the synthesis, morphology and electrical properties of particular nano-engineered carbon nanotube morphology- the Y-junction (Fig. 1), which can be used to lay the foundation for the development of an entirely new class of electronic and opto-electronic devices.

Carbon nanotubes are essentially graphene sheets rolled up into varying diameters [2] and are extremely attractive from both a scientific and a technological perspective, as they are extremely robust (Young modulus approaching 1 TPa) and chemically inert. By varying the nature of wrapping of the graphite sheet and their diameter, nanotubes can be either semiconductors or metals [3] and can be used in electronics [4]. In the literature, there are a variety of tubular structures composed of carbon, and are often referred to as nanotubes (single walled/multi-walled nanotubes: SWNT/MWNT) when the graphene walls are parallel to the axis of the tube, and as nanofibers for other configurations, e.g., where the graphene sheets are at an angle to the tube axis [5]. The electrical and thermal conductivity [6] properties of both SWNTs [7] and MWNTs have been well explored. While SWNTs (diameter ~1 nm) can be described as quantum wires due to the ballistic nature of electron transport [8], the transport in MWNTs (diameter in the range 10–100 nm) is found to be diffusive/quasi-ballistic [9, 10]. Quantum dots can be formed in both SWNTs [11] and MWNTs [9] and the Coulomb blockade and the quantization of the electron states can be used to fabricate single-electron transistors [12]. Several electronic components, based on CNTs, such as single electron transistors (SETs) [12–14], non-volatile random access memory (RAM) [15, 16], and field

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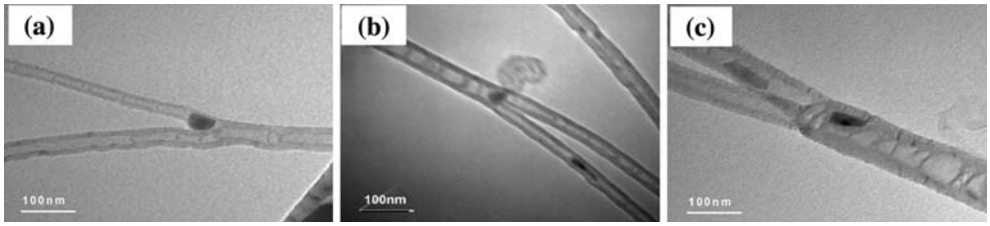

Fig. 1 Carbon nanotube based Y-junction morphologies can be prepared by adding carbide forming elements, such as Ti, Zr, and Hf to ferrocene based thermal CVD (see "Carbon nanotube Y-junction synthesis" section). One can obtain different branching angles (i.e., **a** vs. **b**) and spatial locations of catalyst particles (i.e., **a** vs. **c**) through varying the growth and processing conditions. The detailed geometry is thought to influence the electrical properties of the Y-junctions

effect transistors (FET) and logic circuits [17–19], have been fabricated. However, most of these devices use conventional lithography schemes and electronics principles, either using nanotubes as conducting wires or modifying them along their length. While extremely important in elucidating fundamental properties, the above experiments have used external electrodes, to contact the nanotubes and do not represent truly nanoelectronic circuits. Additionally, the well-known metal oxide semiconductor field effect transistor (MOSFET) architecture is used, where the nanotube serves as the channel between the electrodes (source and drain), and a SiO_2/Si based gate modulates the channel conductance. In other demonstrations, cumbersome Atomic Force Microscope (AFM) manipulations [13] of nanotube properties have been utilized.

It would, therefore, be more attractive to propose new nanoelectronic elements, in order to harness functionalities, peculiar to CNT forms such as nanotubes with bends, Y-junctions [20] etc. One can also envision a more ambitious scheme and circuit topology—where both interconnect and circuit elements are all based on nanotubes, realizing true nanoelectronics. Figure 2 shows one possible realization of an *integrated* nanotube electronics architecture, where several CNT based components are combined for obtaining unique functionalities (the figure represents one way of assembling the CNT based components and is not indicative of a realistic circuit). It is to be noted that CNT based interconnect does not suffer from the problems of electro-migration that plague copper based lines, due to the strong carbon–carbon bonds, and can support higher current densities [21] (~10 μA/nm^2 or 10^9A/cm^2 vs. 10 nA/nm^2 or 10^6 A/cm^2 for noble metals such as Ag). Additionally, the large thermal conductivity [22] (~3,000 W/m K at 300 K), up to an order of magnitude higher than copper, could help alleviate the problem of heat dissipation in ever shrinking devices. Developing nanotube based devices, besides miniaturization and lower power consumption, will allow us to exploit the advantages of inherently quantum mechanical systems, for practical devices, such as ballistic transport and low switching voltages [23] (~26 mV at room temperature $\equiv k_BT/e$).

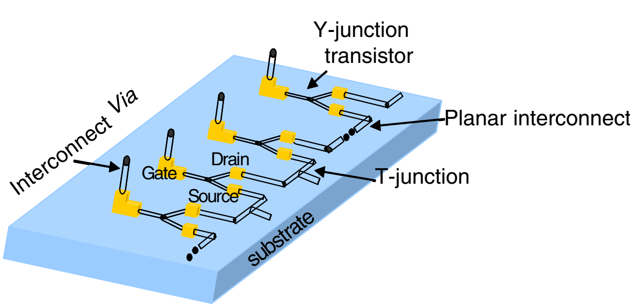

Fig. 2 A conceptual view of a possible CNT technology platform, integrating Y-junction devices, interconnect via and directed nanotube growth. The overall objective is to create nano devices and architecture with novel functionalities that go beyond existing technologies

Branched nanotubes with T-, Y-, L- and more complex junctions (resembling those in Fig. 1), were initially observed in arc-discharge produced nanotubes [24]. Preliminary work on individual Y-junctions, grown through chemical vapor deposition, in a nanochannel alumina template [25] resulted in the observation of non-linear *I–V* characteristics at room temperature through Ohmic contact [26] and tunneling conductance [27] measurements and has opened up a vista of possibilities. We have vastly extended these results through detailed electrical characterization of these junctions as described in our recent publications [20, 28] and are now confident that CNTs/CNT-based structures can be used for active electronic components.

While the current theoretical explanations of the observed electrical behavior in Y-junctions are based on SWNT Y-junctions, the experimental demonstrations detailed in this paper were made on MWNTs [26, 27], which are easier to experimentally manipulate, more mechanically robust, and can form the immediate basis for novel nanoelectronics circuits. MWNTs are generally found to be metal-like [29] with possibly different chiralities for the constituent nanotubes. Currently, there is some understanding of transport in *straight* MWNTs, where it has been shown that electronic conduction mostly occurs through the outermost wall [30], and inter-layer charge transport in the MWNT is dominated by thermally excited carriers [31]. While the outer wall dominates in the low-bias regime (<50 mV), at higher bias many shells can contribute to the conductance with an average current carrying capacity of 12 μA/shell at room temperature [21]. In contrast to SWNTs with μm coherence lengths, the transport in MWNTs is quasi-ballistic [9] with mean free paths <100 nm.

Based on the above brief survey of properties in *straight* MWNTs, we hypothesize that non-coherent electronic transport dominates the Y-junctions and other branched morphologies. We think that our experimental results, presented below, will further advance understanding of the behavior of Y-junctions and other nonlinear CNT forms.

Electron momentum engineering in Y-junctions

One of the early uses of a Y-junction topology, for electronic applications, is the electron-wave Y-branch switch (YBS) [32] where a refractive index change of either branch through electric field modulation was used to affect switching. This device, demonstrated in the GaAs/AlGaAs [33] and InP/InGaAs [34, 35] based two-dimensional electron gas (2-DEG) systems, relies on ballistic transport and is useful for low power, ultra-fast (THz) signal processing. It was derived theoretically [36] and proven experimentally [37] that based on the ballistic electron transport, nonlinear and diode-like *I–V* characteristics were possible. These devices based on III–V materials, while providing proof of concept, were fabricated through conventional lithography. It was also shown in 2-DEG geometries [38] with artificially constructed defects/barriers, that the defect topology can affect the electron momentum and guide the current to a pre-determined spatial location independent of input current direction. This type of rectification involves a new principle of *electron momentum engineering* in contrast to the well known *band engineering*. CNTs provide a more natural avenue to explore such behavior. It was also theoretically postulated [39] that switching and rectification could be observed in symmetric (e.g., no change in chirality from stem to branch) Y-junction SWNTs, assuming quantum conductivity of electrons, where the electrical characteristics could be determined [40] by the

1. formation of a quantum dot/asymmetric scattering center [38] at the location of the Y-junction,
2. finite length of the stem and branches connected to metallic leads,
3. asymmetry of the bias applied/the potential profile [41] across the nanotube, and
4. strength of the nanotube–metal lead interactions.

These criteria have been debated upon [42] in relation to whether the non-linear behavior is *intrinsic* to the Y-junction or is due to the metal contacts. Currently, the influence of contacts and Schottky barrier formation on nanotube properties [43] and rectification is a very active area of research.

Possibility of new applications, using Y-junctions

The motivation for use of new CNT morphologies, either SWNTs or MWNTs, in addition to the miniaturization of electronic circuits, is the possibility of new devices and technologies through new physical principles. New physical regimes of operation arise, for example, through the existence of negative curvature fullerene based units [44], and branching in nonlinear CNTs. In turn, this necessitates the presence of topological defects—in the form of pentagons, heptagons and octagons—at the junction regions for maintaining a low energy sp^2 configuration [45] in the CNT. These *intrinsic* defects are natural scattering centers that could affect/modulate the electrical transport characteristics of a nanotube.

At the nanometer scale, the dimensions of the device are also comparable to electron wavelength (λ_F) and electron travel/current must be considered in terms of wave propagation [46], analogous to the propagation of light down a optical fiber. Wave phenomena, such as interference and phase shifting, can now be used to construct new types of devices. For example, constructive and destructive interferences can be used to cause transmission and reflection of electronic current leading to switching and transistor like applications with added advantage of very low power dissipation. Novel applications have been proposed theoretically [47–49] for ballistic nano-junctions, of which the Y-junction is only one example. Several of these were demonstrated in preliminary experiments and will be elucidated later in the paper. They include:

Switching and transistor applications

In a basic Y-junction switch, an electric field can direct electrons into either of two branches, while the other branch is cut off [23]. It has been shown, in computer simulations [32], that a sufficient lateral field for electron deflection is created by applying a very small voltage of the order of millivolts. The specific advantage of a Y-junction switch is that it does not need single-mode electron waveguides for its operation and can operate over a wide range of electron velocities and energies, the reason being that the electrons are not stopped by a barrier but are only deflected. An operational advantage over a conventional FET is that the current is switched between two outputs rather than completely turned on/off [50], leading to higher efficiencies.

An electrical asymmetry can also be induced through structural or chemical means across the two branches in a nanostructured junction. The Y-junction region, for instance, can possess a positive charge [39] due to two reasons, viz., the presence of: (1) topological defects, due to the formation of non-hexagonal polygons at the junction to satisfy the local bond order [51], where delocalization of the electrons over an extended area leads to a net positive charge, and (2) catalyst particles, which are inevitably present during synthesis [52, 53]. This positive charge and the induced asymmetry is analogous to a ''gating'' action that could be responsible for rectification. While the presence of defects at the junction seems to assist switching, there is also a possibility that such defects may not be needed as we observe some instances of novel switching behavior in Y-junctions without any observable catalyst particles. Additional studies will elucidate these aspects, but such an observation is significant in that a three-dimensional array of Y-junction devices based on CNTs would be much easier to fabricate if a particle is not always required at the junction region.

Rectification and logic function

It is possible to design logic circuitry, based on electron waveguiding in Y-junction nanotubes, to perform operations similar to and exceeding the performance of conventional electronic devices [50]. When finite voltages are applied to the left and the right branches of a Y-junction, in a push–pull fashion (i.e., $V_{\mathrm{left}} = -V_{\mathrm{right}}$ or vice versa), the voltage output at the stem would have the same sign as the terminal with the lower voltage. This dependence follows from the principle of continuity of electro-chemical potential ($\mu = -eV$) in electron transport through a Y-junction and forms the basis for the realization of an AND logic gate, i.e., 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. The change of μ is also not completely balanced out due to the scattering at the junction, and results in nonlinear interaction of the currents from the left and the right sides [37]. To compensate, the resultant center branch voltage (V_S) is always negative and varies parabolically (as V^2) with the applied voltage-V [47].

Harmonic generation/frequency mixing

The non-linear interaction of the currents and the parabolic dependence of the output voltage at the junction region also suggest the possibility of higher frequency/harmonic generation. When an AC signal of frequency ω, $V_{\mathrm{L-R}} = A \cos [\omega t]$, is applied between the left (L) and right (R) branches of the Y-junction, the output signal from the stem (V_S) would be of the form: $V_S = a + b \cos [2\omega t] + c \cos [4\omega t]$, where a, b and c are constants.

The Y-junction can then be used for second and higher harmonic generation or for frequency mixing [34]. The second harmonic (2ω) output is orthogonal to the input voltage and can be easily separated out. These devices can also be used for an ultra-sensitive power meter, as the output is linearly proportional to V^2 to very small values of V. A planar CNT Y-junction, with contacts present only at the terminals, suffers from less parasitic effects than a vertical transistor structure and high frequency operation, up to 50 GHz at room temperature [54], is possible.

It can be seen from the brief discussion above that several novel devices can be constructed on CNT Y-junction technology, which could be the forerunner of a new paradigm in nanoelectronics.

Carbon nanotube Y-junction synthesis

It is to be noted at the very outset that the Y-junctions synthesized are quite different in form and structure compared to crossed nanotube junctions [55], where the nanotubes are individually placed and junctions produced through electron irradiation [56].

The Y-junction nanotubes have been grown [53] on bare quartz or SiO_2/Si substrates through thermal chemical vapor deposition (CVD). A mixture of ferrocene ($C_{10}H_{10}Fe$), xylene ($C_{10}H_{10}$) and a Ti containing precursor gas-$C_{10}H_{10}N_4Ti$ was decomposed at 750 °C in the presence of flowing argon (~600 sccm) and hydrogen (75 sccm) carrier gases. The CVD reactor consists of two stages: (1) a low temperature (~200 °C) preheating chamber for the liquid mixture vaporization followed by (2) a high temperature (~750 °C) main reactor. A yield of 90% MWNT Y-junction nanotubes, which grow spontaneously on quartz substrates in the main reactor, was obtained. The mechanism for the Y-junction growth is hypothesized to depend on the carbide forming ability of Ti as measured by its large heat of formation (ΔH_f of –22 Kcal/g atom). The Ti containing Fe catalyst particles seed nanotube nucleation and grow by a *root growth* method, in which carbon is absorbed at the root and then ejected to form vertically aligned MWNTs (Fig. 3a). As the supply of Ti-containing Fe catalyst particles continues (Fig. 3b), some of the particles (Fe–Ti) attach onto the sidewalls of the growing nanotubes (Fig. 3c). The catalysts on the side then promote the growth of a side branch (Fig. 3d), which when further enhanced forms a full fledged Y-junction. The correlation of the carbide forming ability to branch formation is also supported by Y-junction synthesis in Hf- and Zr-doped Fe catalyst particles [53], which also have large ΔH_f (HfC: –26 Kcal/g-atom and ZrC: –23 Kcal/g atom) It is generally found that the use of Zr and Hf catalysts yield larger diameter Y-junctions.

The ratio of the Ti-precursor gas and the feedstock gases could be adjusted to determine the *growth of the side-branches at specific positions*. For example, a decreased flow of the xylene gas, at a point of time, would halt the growth of the nanotube, while preponderance of the Fe–Ti precursor gas/catalyst particles would nucleate the branch. The Y-junction formation has also been found to be sensitive to temperature, time and catalyst concentration. The optimal temperature range is between 750 and 850 °C; below 750 °C, the yield is very low and temperatures greater than 850 °C produce V-shaped nanotube junctions. Y-junction CNTs with minimal defects were obtained when the atomic compositions of Fe:Ti:C was in the ratio 1:3:96.

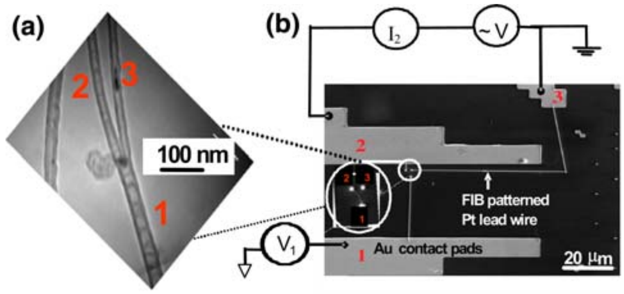

Fig. 4 (**a**) A MWNT Y-junction electrical measurement configuration as imaged in the (**b**) SEM. The electrical contacts on the Y-junctions are performed through a focused ion beam deposition (*FIB*) procedure (see text)

The growth of the Y-junctions essentially seems to be a non-equilibrium phenomenon and various other methods have been found to be successful in proliferating branches, such as sudden reduction of temperature during a normal tip growth process [52], where over-saturation by the carbon feedstock gas causes a surface energy driven splitting of the catalyst particle and branch nucleation. Other catalyst particles, such as Ca and Si, have also been found to nucleate side branches [25]. The location of the junction is, in any case, a point of structural variation [57] the control of which determines the formation of Y-junctions.

Electrical transport measurements

Rectification and abrupt electrical switching characteristics

We have conducted preliminary experiments to probe the electrical characteristics (DC and AC measurements) of the Y-junctions. These were very promising and portend the potential use of these Y-junctions in nanoelectronics.

The samples for electrical measurements were prepared by suspending nanotube Y-junctions, made through CVD (Figs. 1, 4a), in isopropanol and depositing them on a SiO_2/Si substrate with patterned Au

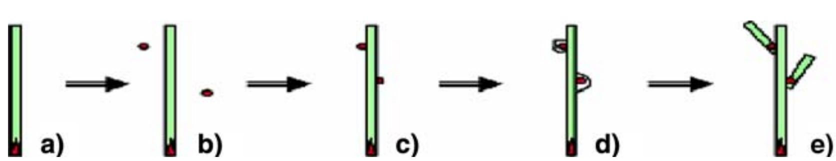

Fig. 3 The postulated growth sequence of a Y-junction nanotube [53] involves: (**a**) initial seeding of a straight nanotube through conventional catalytic synthesis [52], (**b**) Ti-doped Fe catalyst particles (from ferrocene and $C_{10}H_{10}N_4Ti$) attach (**c**) to the sidewalls and nucleate (**d**) the side branches (**e**)

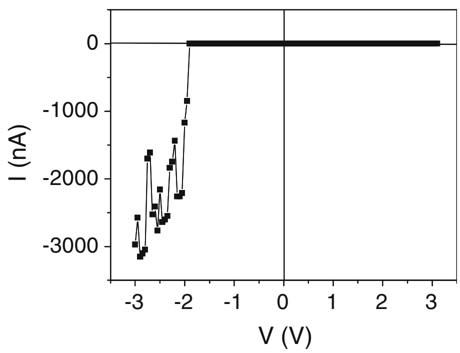

Fig. 5 Current rectification behavior obtained in CNT Y-junctions illustrates their possible application as diode elements in nanoelectronic circuits. Such rectification is plausible when the space charge characteristics dominate over the Ohmic transport in the CNT geometry

pads. Y-junctions, in proximity to the Au contact pads, were then located at low voltages (<5 kV) using a scanning electron microscope (SEM) equipped with a focused ion beam (FIB). The ion-beam in the FIB-SEM was used to deposit Pt, which connects the Y-junction terminals to the contact pads (Fig. 4b). Special care was taken to not expose the nanotube to the ion-beam, to prevent radiation damage [58]. A Wentworth probe station, with needle contacts [43], was used to apply voltages and measure the currents. Phase sensitive (AC) measurements using a lock-in amplifier (Stanford Research systems: SR830) were also performed [29, 31].

By grounding each branch of the Y-junction successively, we were able to probe the inter- and intra-branch resistances. Several samples were tested with reproducible results. When measured pair-wise, the average resistance of the combined branches was ~100 kΩ. While MWNTs should theoretically have a resistance much smaller than h/e^2 (~26 kΩ), ideal Ohmic contacts, through metal evaporation, are difficult to achieve. However, local electron exposure onto the CNT-Ohmic contact has been shown [59] to reduce contact resistances, and is a possible solution to achieving better contacts in the near future. We are in the process of characterizing the origin of the capacitive and inductive components of the impedance and our research is aimed to yield good insights into their physical origins. We were also successful in establishing the diode behavior (with an ON/OFF ratio >10^4) of the CNT Y-junction branches, with excellent current blocking behavior (Fig. 5), the details of which will be published soon.

Additionally, we explored the possibility of using the CNT Y-junctions for switching applications as an electrical inverter analogous to earlier [32, 35, 37] Y-switch studies in two-dimensional electron gases. In this measurement, a DC voltage was applied on one branch of the Y-junction while the current through the other two-branches was probed under a small AC bias voltage (<0.1 V). As the DC bias voltage is increased, at a certain point the Y-junction goes from nominally conducting to a ‘‘pinched-off’’ state. This switching behavior was observed for all the three-branches of the Y-junction, at different DC bias voltages. The absolute value of the voltage at which the channel is pinched off is similar for two branches (~2.7 V, as seen in Fig. 6a, b), and is different for the third stem branch (~5.8 V, as in Fig. 6c). The switching behavior was seen over a wide range of frequencies, up to 50 kHz, the upper limit being set by the capacitive response of the Y-junction when the branch current tends to zero.

In our experiments, if it is assumed that the Ohmic resistance for all the three contacts is identical, it is possible to identify the individual branch's transport characteristics. (It was not possible to determine all the four impedances: Z_1, Z_2, Z_3 and the contact resistance with currently used three-terminal measurements). A more in-depth analysis of the contributing factors to the electrical conductivity of a Y-junction is thus possible, e.g., an increased resistance R_1 (see Fig. 4a) could result from the presence of a catalyst particle in the stem-section.

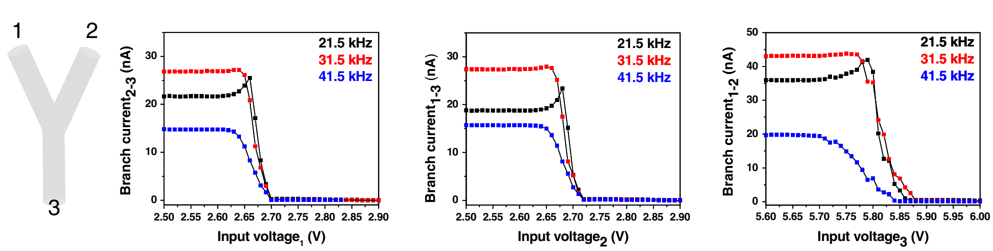

Fig. 6 An abrupt modulation of the current through two branches of the Y-junction, indicative of electrical switching, is seen on varying the voltage on the third branch. The voltage, at which the switching action occurs, on the two branches (*1* and *2*), is similar and smaller (~2.7 V, see **a** and **b**) compared to the turn-off voltage (~5.8 V) on the stem (*3*) in (**c**)

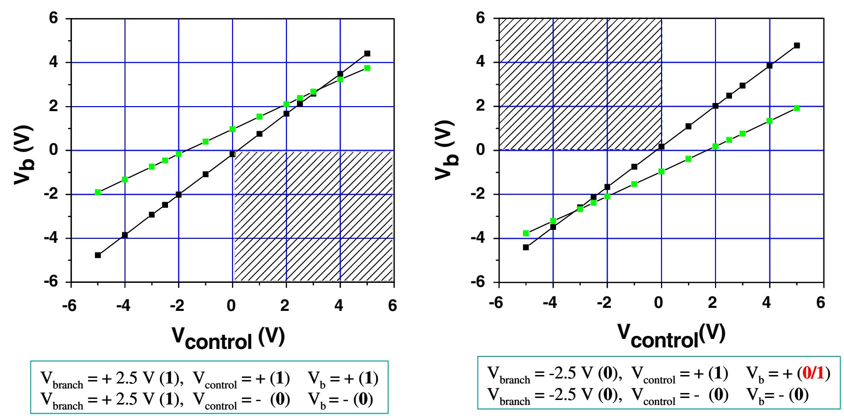

Fig. 7 The carbon nanotube Y-junction can be used for logic applications, as an AND logic gate. The two lines (*green* and *black*) refer to the possible permutations of the voltages applied on the two branches (*1* and *2* in Fig. 6)

We were also able to obtain preliminary evidence of AND logic gate behavior (Fig. 7)—see ''Rectification and logic function'' section for a detailed explanation. The continuity of the electro-chemical potential from one branch of the CNT Y-junction to another is the basis. 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 DC voltage (V_{control}) is swept across the third branch of the Y-junction. The intermixing of the currents between the three branches could be responsible for the partial realization of an AND gate.

The logic characteristics are not perfect, however, due possibly to details [60] of the nanostructure and it would be pertinent to determine the Y-junction morphology for realizing *ideal* logic gate behaviors.

The detailed nature of the electrical switching behavior is not understood at present. The presence of catalyst nano-particles (Fig. 1) in the conduction paths could 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, which suggests the possibility of nano-engineering the Y-junction to get a variety of switching behaviors. An alternative possibility is that there is inter-mixing of the currents in the Y-junction, where the electron transmission is abruptly cut off due to the compensation of currents, for example, the current through branches 2 and 3 is cancelled by current leakage through stem 1 (see Fig. 4a). The simultaneous presence of an AC voltage on the source–drain channel and a DC voltage on the control/gate terminal could also result in an abrupt turn-off, due to defect mediated negative capacitance effects [61]. Further research is needed to clarify the exact mechanisms in these interesting phenomena.

Current blocking behavior

Other interesting characteristics were seen when the CNT Y-morphologies were in situ annealed in the ambient, in a range of temperatures 20–400 °C and I–V characteristics measured for various configurations of the Y-junction. The observations are summarized in Fig. 8 and are fascinating from the point of view of tunability of electrical behavior (S1 is the stem of the Y-junction while B2 and B3 refer to the branches). We believe that [62] the observed curves are indicative of the interplay of space-charge currents and contact behavior in the Y-geometry. The geometry/topology of the Y-junction geometry could also be playing a role. We model this behavior in terms of the relative importance of the Ohmic current or space charge limited electrical transport. The relative magnitudes of the dielectric relaxation time (t_{d}) and the carrier transit time (t_{tr}) dictate [63] which type of current flow predominates in a nanostructure. A larger $t_{\mathrm{tr}}/t_{\mathrm{d}}$ ratio,

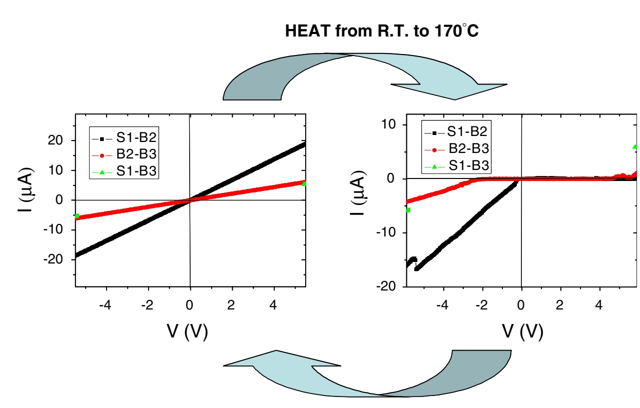

Fig. 8 Reversible current blocking behavior induced in the CNT Y-junction. The individual segments' (*S*: stem, *B*: branch) electrical transport characteristics exhibit different blocking/linear characteristics, which are geometry dependent

obtained, say at smaller voltages would result in Ohmic currents while a lower ratio would imply space-charge limited currents. As t_d is inversely proportional to the conductivity, these effects would assume greater importance at elevated temperatures. Further details of these interesting characteristics will soon be published.

Topics for further investigation

(a) The detailed morphology of the Y-junctions and their effect on the electrical properties needs to be more fully characterized. Catalyst particles have been found both at the junction, along the length of the Y-junctions and at the tips [25] (Fig. 1). The effect of the location, type, and composition of these particles and their scattering characteristics on the electrical transport would yield insight into their influence.

(b) Many details of the growth mechanisms of multi-junction CNT are not clear vis-à-vis the influence of the catalyst particles. It has also been contended [52] that a perturbation during growth could promote the formation of branches/junctions. For example, if the temperature is reduced during the growth process, a catalyst particle over-saturated with carbon can be induced to nucleate another branch. On the other hand, if the Ti catalyst does play a role, the importance of carbide formers in inducing side-branch growth is interesting from a basic thermodynamic point of view (also, see "Carbon nanotube Y-junction synthesis" section). It is worth noting that Y-junctions and other morphologies, such as H-junctions and T-junctions [57], are also formed when methane (negative ΔH_f) is used as a precursor. The composition of the catalyst particle, which nucleates the nanotube branches [52], and the effects of stress generated at the growing nanotube tips could also have a crucial role [57] in Y-junction growth.

(c) The issue of electrical conductivity through nanotubes with bends, junctions, and catalyst particles is a very important topic of study and will also determine the future viability of nanotube based electronics and interconnect. While the MWNT has an intrinsic resistance, say due to ballistic transport, a capacitive and inductive component will also have to be considered due to the presence of particles, inter-tube transport etc. Such a study will also yield insight into the speed of operation of the nanotube based devices and affecting factors, in terms of the RC delay. It has been theoretically proposed [64] that *straight* SWNTs are capable of THz operation and can even be used as nano-antennae [65] for radiation and detection in these very high frequency ranges. While MWNT Y-junctions may not have such high frequency resonances, due to the presence of defects, an ultimate limit [66] of their performance is worth studying.

(d) It has been proposed [60], based on our seminal work [20], that novel CNT based circuits based on Y-junctions and branched morphologies can be created. These circuits could be fabricated so as to construct universal logic gates such as NAND/X-NOR. Such a demonstration together with the possibility of multi-functionality, where the catalyst particle can be used as a single photon detector [67] in Y-junction morphologies will be important. A variety of such novel circuits can be fabricated leading to a potentially new paradigm for nanoelectronics that goes well beyond traditional FET architectures, yielding, for example *shape controlled logic elements*.

(e) Assembly into a viable circuit topology and large scale fabrication are issues that are of paramount importance. Currently, the Y-junctions are grown in mats/bundles and individually isolated and measured. A scheme where each junction is assembled in this way is not viable for practical fabrication. Ideas into self-assembly and controlled placement [68] of nanotubes will have to be addressed. While some measure of success has been achieved in coordinating the placement of loose nanotubes, e.g., through the use of chemically functionalized substrates [69] along with dip-pen lithography [70], an orienting electric field-exploiting the nanotubes' dipole character [71], through magnetic field [6], and microfluidic arrangements [72], assembly of such loose nanotubes is difficult to scale up and still remains a critical issue. A possible scheme using electric field controlled growth for Y-junction growth is outlined in Fig. 9. An array of Y-junctions can be prepared on the same nanotube stem, as was found in our preliminary studies, by exposing only periodic locations along the length of a nanotube, sputter depositing catalyst, and growing parallel Y-junction branches from these linear array of catalysts using electric field induced direction control during subsequent CVD process, e.g., at any angle from the main stem.

The above growth technique could be used to make multiple Y-junction devices in series/parallel. This

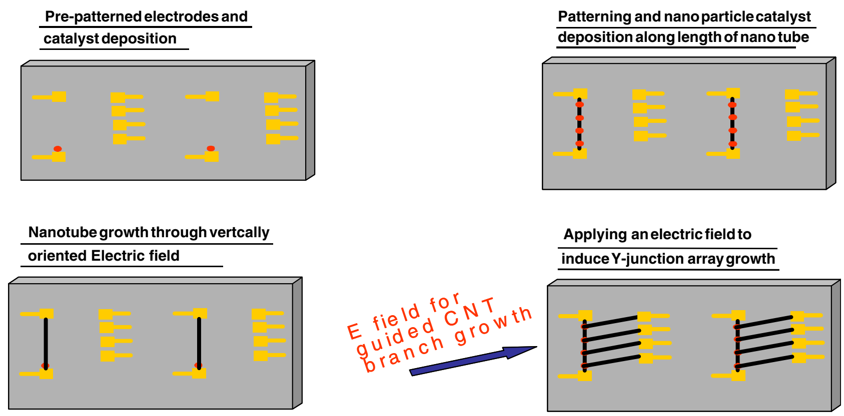

Fig. 9 A suggested method for the synthesis of location-specific, controlled Y-junction growth for arrayed electronic circuitry, which can be accomplished by the use of a bias electric field in thermal CVD processes

proof of growth will go a long way in demonstrating the feasibility of large scale nanoelectronic device assembly—a question of the highest importance in recent times. Alternately, growing self-assembled branches at various angles on the CNTs can provide a ready-made template for large scale synthesis of Y-junctions.

Conclusions

The Y-junctions that have been investigated represent one of the first attempts in realizing a nanoelectronic device from CNTs alone, without the need for an external gate. This represents a major departure from the MOSFET paradigm and we hope that this could lead to widespread investigation of CNT based materials and morphologies for multi-functional architectures. In preliminary experiments, several interesting electrical characteristics for the Y-junctions including (1) rectification/current blocking behavior, (2) rapid electrical switching and (3) logic gate characteristics, were seen. Future experiments will correlate detailed physical structure of the CNT junction morphologies to the electrical measurements to gain a better understanding of the conduction processes vis-à-vis the role of defects and geometry in nonlinear structures. It is also possible to nano-engineer the CNT morphologies through modified growth processes and in situ manipulation through electron beams. These studies will pave the way to the realization of various electronic and opto-electronic devices using paradigms exclusive to the nanoscale.

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