Differential current amplification in three-terminal Y-junction carbon nanotube devices

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We present three-terminal transistor-like operation of Y-junction carbon nanotubes with three independent contacts. Using one of the terminals as a controlling gate, differential current gain of up to 300 is observed at low temperature (4.2 K) in the biasing region where the gate current is small. We present evidence that the observed transistor characteristics can be ascribed to a new amplification mechanism: gated hopping via conducting grains. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2048812]

Carbon nanotubes (CNTs) have been the focus of intense scrutiny because of their unique and potentially superior electronic properties.[1–3] While highest quality CNT material is produced by laser ablation and arc discharge, nanotubes produced using chemical vapor deposition (CVD) with the use of nanotemplates to control the size and position of the material are central to device integration.[4,5] Especially interesting is the possibility of producing multiterminal nanodevices, which have shown some promise in theory and experimental observation.[6–10]

In CVD CNTs grown in nanotemplates, aluminum substrates are anodized under special conditions to produce regular pores with a spacing and diameter of approximately 50 nm. After the deposition of a magnetic catalyst, these nanopore templates are exposed to carbon carrying gases such as acetylene at approximately 600 °C. The deposition of carbon material in the catalyst produces regular arrays of multiwalled carbon nanotubes.[11]

Previously, Li *et al.* have reported that by varying the anodization conditions while manufacturing these nanotemplates, it is possible to get one larger pore to branch into two smaller ones.[9] Such nanotemplates can then be used to produce Y-junction CNTs, with two smaller branches connected to a larger stem, as shown in Fig. 1(a). In the original work characterizing the electrical properties of such Y-junctions, two-terminal $I(V)$ measurements of the material were made while the tubes remained in the template, as well as after they were removed from the matrix and placed on predefined contacts. The measurements showed an electrical rectifying behavior that was attributed to a heterojunction where the nanotubes join, due to a mismatch between the band gap of the larger stem and the smaller branches.[10,12]

In this work, we report the first three-terminal transistor operation of Y-junction CNTs with independent contacts. Using e-beam lithography and palladium (Pd) metallization,[13] we have made separate contacts to the Y-junction branches, as shown in Fig. 1(a). The nanotubes were dispersed on a thick SiO_2-covered silicon substrate prepatterned with alignment marks. Candidate Y-junction CNTs with split branches were found by scanning electron microscopy (SEM), six-contact patterns were written, and Pd contacts were lifted off using e-beam lithography. Subsequently, large secondary Ti/Au bonding pads were patterned. The six contacts allow us to characterize the material and the contacts separately. The diameter of the larger stem is ~50 nm and that of the smaller branches is ~30 nm, as verified by SEM.

To investigate three-terminal characteristics of the Y-junction CNTs, we took $I_D(V_D,V_G)$ measurements (D = drain; G = gate) using the inner three contacts, in the geometry shown in Fig. 1(b). At T=300 and 77 K, linear behavior was seen consistent with ohmic contacts and diffusive transport, with no current gain. At T=4.2 K, at fixed V_D we observe a change in I_D that is much larger than the associated change in the gate current I_G as V_G is scanned near $V_D/2$ (where the gate terminal current I_G is at a minimum). The resulting differential current gain can be quantified by taking the numerical derivative of the $I_D(V_G)$ and $I_G(V_G)$ character-

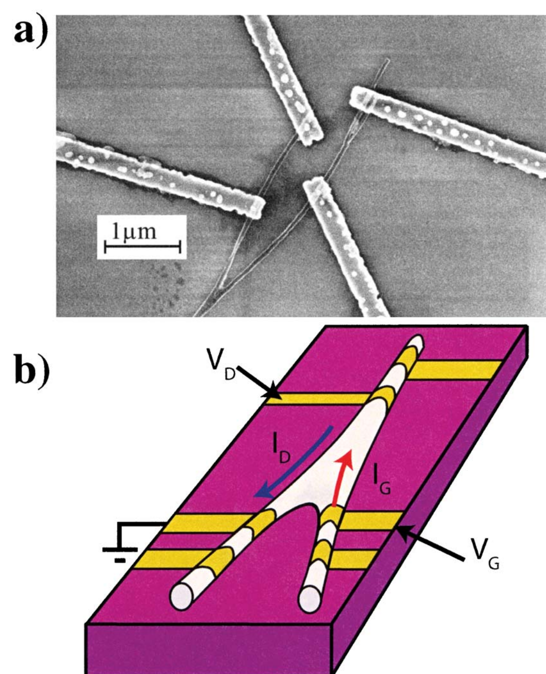

FIG. 1. (Color online) (a) SEM micrograph of the independent Pd contacts to the branches of a Y-junction fabricated using e-beam lithography. Subsequent lithography is done to produce larger Ti/Au bonding pads. (b) Schematic measurement geometry for the three-terminal $I_D(V_D,V_G)$ measurements. Additional four-point $I(V)$ measurements were used to characterize the junction conductance, with the remaining third terminal left floating.

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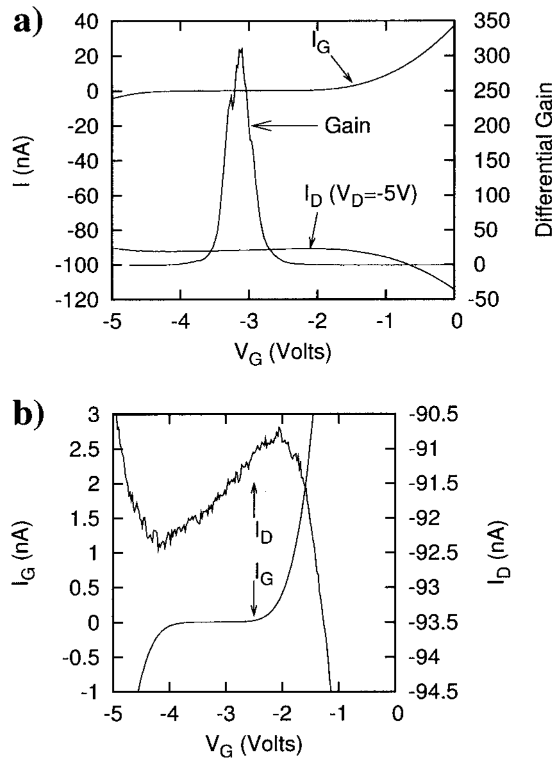

FIG. 2. (a) Three-terminal $I_D(V_G)$ and $I_G(V_G)$ curves for the device shown in Fig. 1 for fixed $V_D=-5$ V. The differential conductance is calculated by taking the ratio of the I_D and I_G slopes averaged over 0.5 V in V_G. (b) A closeup of the same measurements with I_D offset to show the relatively large change compared with I_G.

istics and taking the ratio. The results are summarized in Fig. 2, showing the maximum differential gain of ~300. The derivatives are averaged over a 0.5 V range to reduce noise [see Fig. 2(b) for a close-up of the currents]—this reduces the peak value of the differential gain.

This differential current gain can be observed regardless of the choice of gate terminal of the device; that is, all three terminals can work as a gate, although the magnitude of the gain varies. The observed differential gain is independent of the rate at which the gate voltage is ramped, ruling out capacitive effects. It is reproducible over repeated measurements, but the magnitude changes with temperature cycling, which is suggestive of charge trapping. It is worth noting that although the measured external gain is not large from a device perspective, there is a significant internal series resistance of the CNT material between the contacts and the Y-junction. Since the junction area constitutes only a small fraction of the overall device length (on the order of 0.1 μm compared with ~5 μm total separation between the contacts, see Fig. 1), the conductance change in the actual Y-junction is quite large.

In order to further characterize current transport through the Y-junction region, we have measured four-terminal $I(V)$ characteristics at $T=300$, 77, and 4.2 K. Representative stem-to-branch $I(V)$ curves, measured with the third terminal floating, are shown in Fig. 3. At $T=300$ and 77 K, the $I(V)$ curves are ohmic, with Pd contact resistance representing a small fraction of the CNT material resistance (the total contact resistances are ~600 and ~3.5 MΩ compared to the CNT resistances of ~4.2 and ~16 MΩ at $T=300$ and 77 K, respectively). Measurements taken at $T=4.2$ K show nonlinear characteristics with a contact resistance of ~20 MΩ and

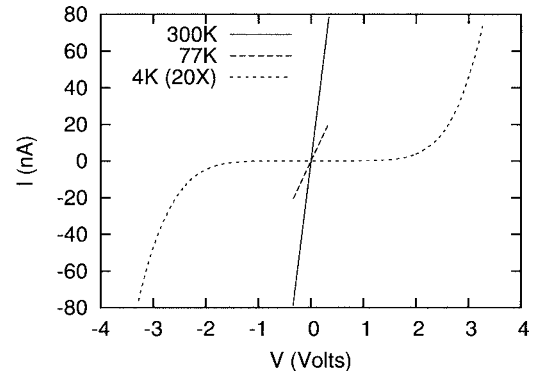

FIG. 3. $I(V)$ characteristics of the right branch to stem of a Y-junction, with the other branch left floating at $T=300$, 77, and 4.2 K (the 4.2 K curve is multiplied by 20 for clarity), corrected for the ohmic contact resistance.

CNT material resistance of ~400 MΩ, with negligible asymmetry, as shown in Fig. 3. No rectification corresponding to nanotube diameter change is observed.

The nonlinear behavior at low temperature and the very high zero bias resistance at $T=4.2$ K, as well as the temperature dependence of the low-field conductance G, is consistent with hopping conduction in granular films.[14–16] The theory proceeds from the assumption that the material is composed of variable sizes of grains, and the ratio of grain size d and separation s is approximately constant. At higher temperatures, the charging energy is lower than kT and carriers can hop between all islands. As the temperature decreases, the smallest islands no longer contribute to conduction, since their charging energy becomes higher than kT. A schematic of this process is shown in the lower inset of Fig. 4. Since the larger islands are further apart, this leads to the ratio of grain size and separation being roughly constant. This theory, originally developed for granular metals by Sheng and Abeles,[14–16] makes specific predictions for the temperature and electric-field dependence of the conductivity. The low

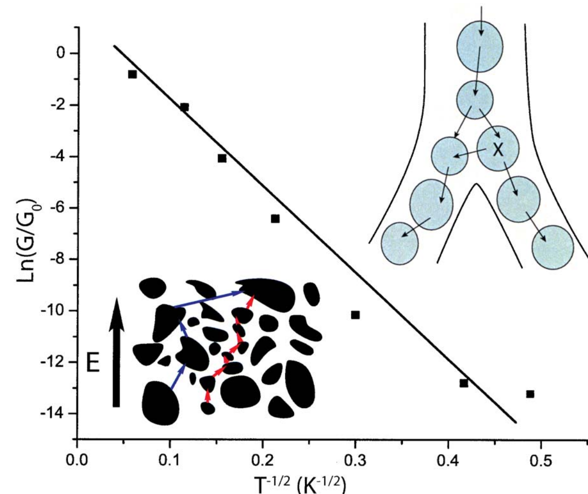

FIG. 4. (Color online) Temperature-dependent conductivity of template grown CNT material at low electric field, plotted as $\ln(G/G_0)$ vs $T^{-1/2}$, where G_0 is the room-temperature conductivity. Lower inset shows a schematic picture of granular hopping conduction (red and blue arrows correspond to higher and lower temperature hopping conduction paths, respectively). Upper inset shows a schematic of island charging due to V_G gating the source-drain hopping conduction: a small current I_G changes the potential of grains within the Y-junction area, thereby controlling the hopping source-drain current and leading to differential current gain.

electric-field conductivity is described by[15,16]

$$G(T) = G_0 \exp[-2(C/kT)^{1/2}], \quad (1)$$

where G_0 is approximately a constant that depends on the density of the current paths, and C is a parameter that depends on the grain charging energy and the characteristic decay length of the carrier wavefunction between the grains. Figure 4 plots $\ln(G/G_0)$ against $T^{-1/2}$, showing reasonable agreement with Eq. (1). From these measurements, as well as the electric field dependence of the conductivity (to be reported elsewhere), we estimate a graphite grain size $d \sim 10$ nm. This is less than but not negligible compared to the CNT diameter, suggesting that the gate voltage applied on one terminal can influence the potential of a significant number of hopping sites at the Y-junction. Small bias changes on the control electrode charge the junction region, which create larger changes in the tunneling rate between islands along the source-drain conducting path, as shown schematically in the upper inset of Fig. 4. The resulting change in the source-drain current flow leads to differential current gain.

Other recent work has indicated that straight nanotubes grown in templates have a highly defective structure that leads to two-dimensional variable range activated hopping conduction at low T.[17] In that model, carriers are trapped on defect states and use thermally activated tunneling to travel between defects. Additional measurements of conductance as a function of electric field, temperature, and magnetic field will be necessary determine the exact transport mechanism in the novel geometry of a grainy cylindrical current-carrying surface that describes CNTs.

Other methods of producing Y-junction CNTs have been reported.[18–20] Since it appears likely that most Y-junction CNTs will have defects in the junction area, and given the vital importance of three-terminal devices in electronics, investigations into how these defects may contribute to device characteristics are essential to advance the technology and our understanding of the underlying physical mechanisms.

In summary, we have measured three-terminal transistor characteristics of a Y-junction CNT device with independent contacts to the stem and the branches, and observed significant differential current gain at low temperature. The temperature dependence of the junction resistance is consistent with granular hopping conduction, which provides a mechanism for current amplification in the Y-junction area.

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