Local Gate Effect of Mechanically Deformed Crossed Carbon Nanotube Junction

Quan Qing,† Daniel A. Nezich,§ Jing Kong,∥ Zhongyun Wu,† and Zhongfan Liu*,†

†Beijing National Laboratory for Molecular Sciences, State Key Laboratory for Structural Chemistry of Unstable and Stable Species, College of Chemistry and Molecular Engineering, Center for Nanoscale Science and Technology, Peking University, Beijing, 100871, China, ‡Department of Chemistry and Chemical Biology, Harvard University, Cambridge, Massachusetts 02138, United States, and §Department of Physics and %Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, United States

ABSTRACT In this work, we have demonstrated that the local deformation at the crossed carbon nanotube (CNT) junctions can introduce significant tunable local gate effect under ambient environment. Atomic force microscope (AFM) manipulation of the local deformation yielded a variation in transconductance that was retained after removing the AFM tip. Application of a large source–drain voltage and pressing the CNT junction above a threshold pressure can respectively erase and recover the transconductance modulation reversibly. The local gate effect is found to be independent of the length of the crossed CNT and attributed to the charges residing at the deformed junctions due to formation of localized states. The number of localized charges is estimated to be in the range of 10^2 to 10^3. These results may find potential applications in electromechanical sensors and could have important implications for designing nonvolatile devices based on crossed CNT junctions.

KEYWORDS Carbon nanotube, crossed-junction, localized charges, transconductance modulation

Carbon nanotubes (CNTs) have been extensively studied in the past decade as a promising building block for high-performance field effect transistors (FETs) and interconnects. In particular, crossed nanotube architectures are proposed as a bottom-up approach for scalable nanoelectronics, such as random access memory and address decoders for integrated nanosystems due to their intrinsically small feature size and tunable junction properties. Most studies on crossed carbon nanotubes have been focusing on the intertube transport properties. Specifically, people have studied the junction conductance and Schottky barrier between different types of CNTs for single cross junctions, as-grown Y-shaped CNTs, and within CNT networks. In addition, the Luttinger liquid behaviors in dispersed samples, as well as CNT buckles and crossings formed by atomic force microscope (AFM) manipulation. Both experiments and theories propose that the structural deformation at the CNT junctions be critical for explaining the observed intertube conductance and the local pressure could induce semiconducting to metallic CNT transition as evidenced by elastic and inelastic scanning tunneling spectroscopy. Only a few reports have looked into the delicate transconductance hysteresis introduced by the charge exchange process between the channel CNT and isolated crossed CNTs or nanoparticles that are in contact with it. Moreover, all these studies were performed at low temperatures, and the contact junctions were simply treated as a tunneling barrier. Although localized states are known to form at crossed CNT junctions and could modulate the transport properties of the underlying CNT FET unit, no data have been reported to show such behaviors under ambient environment, which is required toward practical applications of crossed CNT devices. Here we demonstrate for the first time that as-grown crossed CNT junctions can have clear modulation on the transconductance of the CNT FET at room temperature, and such modulation is sensitive to the mechanical disturbance to the junction. These results may find potential applications in electromechanical sensors, and could have important implications for designing nonvolatile devices based on crossed CNT junctions.

The overall experiment setup is illustrated in Figure 1a. We fabricated a CNT FET by making metal contacts on both ends of a semiconducting CNT (sCNT). An as-grown crossed CNT (cCNT), isolated from both electrodes, was in contact with the sCNT to form a crossed junction (see Methods in Supporting Information). An AFM tip was used to mechanically deform the CNT junction or change the position of the CNT, and the transport property of the sCNT was monitored before and after the manipulation using the bulk degenerated silicon substrate as the back gate. The AFM image of a typical device is shown in Figure 1b. We highlight several important transport characteristics of a typical FET device in Figure 2a–d. First, all CNT FET devices demonstrated p-type behavior as commonly observed in air with an on–off ratio I_{on}/I_{off} ~ 10^3. When the...
gate voltage \( V_g \) was scanned from -20 to +20 V (forward direction) with a constant source–drain voltage \( V_{ds} = 0.1 \) V, the source–drain current \( I_{ds} \) clearly deviated from the linear slope and reached a plateau tail between -10 and -5 V before the sCNT was depleted (Figure 2a, black trace on the left, more discussion on this in Figure 3). Second, an AFM tip was used to press the crossed CNT junction at 0.30 GPa for 1 s and then released. As a result, the transconductance turned positive between \( V_g = -12 \) to -10 V, and then back to negative again, producing a significant current peak between -12 and -4 V (Figure 2a, red line on the left). We note that these features were very brief and insignificant when sweeping \( V_g \) in the reversed direction from +20 to -20 V (Figure 2a, black and red lines on the right, and Supporting Information Figure S3). The hysteresis between the scans of opposite directions is attributed to the water molecules absorbed on the surface of sCNT. Third, we performed a series of AFM pressing and releasing operations at the CNT junction of the same device with incremental pressure intensities, and plotted the \( I_{ds} - V_g \) traces after each AFM manipulation in Figure 2b (the forward \( V_g \) scans). Clearly, the negative-to-positive transconductance transition only appeared after a pressure threshold of approximately 0.30 GPa was reached (Figure 2b, red trace). Fourth, after each \( I_{ds} - V_g \) scan of Figure 2b, the source–drain current \( I_{ds} \) was measured as a function of \( V_{ds} \) from 0 to 10 V at \( V_g = -20 \) V. Three representative results are shown in Figure 2c, including the results from the original FET device, after pressing at 0.12 GPa and after pressing at 0.40 GPa, respectively. All the traces showed a saturation current of about 35 \( \mu \)A\(^{18}\) after \( V_{ds} = 6 \) V and no significant difference in their shapes, indicating that there was no structural damage to the sCNT after the AFM manipulation. Last, such 0–10 V \( V_{ds} \) ramping erased the transitional transconductance fluctuations in the \( I_{ds} - V_g \) traces. Figure 2d compares the \( I_{ds} - V_g \) traces of the original device (black trace) after pressing at 0.30 GPa (red trace), which showed the peak between -12 and -4 V, and after the 0–10 V \( V_{ds} \) scan (blue trace) where the peak disappeared. More significantly, the transitional peak in the \( I_{ds} - V_g \) traces can be reversibly recovered by the AFM operation and erased by applying a large \( V_{ds} \) bias over 3 V. Over 20 cycles of erasing and recovering have been tested on the same device with reproducible results and no major changes of features or degradation. No erasure of the \( I_{ds} - V_g \) features have been observed if \( V_{ds} < 1 \) V was applied. The transconductance modulation is most obvious for \( V_{ds} \) between -0.4 and 0.4 V and become less apparent for larger \( V_{ds} \) (0.4 V < \(|V_{ds}| < 1 \) V). The position and the shape of the peak did not show significant changes under ambient environment within a week (Supporting Information Figure S1).

It is important to note that the AFM manipulation only served to change the shape of the transitional transconductance features from a plateau tail (Figure 2d, black trace, \( V_{ds} \) between -10 to -4 V) to a peak (Figure 2d, red trace, \( V_{ds} \) between -12 to -4 V), or to recover it after the erasure. The existence of such features was only determined by the formation of the crossed junction. In other words, the modulation of transconductance before the device is turned off can be commonly observed in the majority of the crossed devices that we have studied when (1) only small \( V_{ds} \) (0.1 V) has been applied and (2) without performing any AFM manipulation. Figure 3a gives a typical example where the original device with the as-grown crossed junction exhibited the plateau tail between \( V_g = -12 \) and -6 V (blue trace). Upon removal of the sCNT (marked by * in the inset of Figure 3a) with an AFM tip, the tail vanished and the device shut down at about -14 V (Figure 3a, red trace). In addition, Figure 3b shows another type of device that directly demonstrated a negative-to-positive transconductance transition with the as-grown crossed junction. The \( I_{ds} - V_g \) trace (blue trace) displayed a clear transitional positive transconductance between \( V_g = -25 \) and -24 V. When the sCNT was shifted about 100 nm away from the original crossing point (Figure 3b, inset AFM image) by pushing along the right side of the sCNT with an AFM tip, possibly loosening the CNT–CNT contact, such characteristics disappeared immediately (Figure 3b, red trace). The clear dependence of the transitional transconductance features on the tight formation of crossed junctions strongly suggests that the modulation of transconductance both for the original crossed CNT devices and after AFM manipulation share the same mechanism.

Furthermore, the modulation of the transconductance is not correlated to the length of the cCNT within the range that...
we have investigated, as illustrated in Figure 3c. The length of the cCNT was approximately 6 µm after isolating both of its ends from the electrodes with AFM manipulation (Figure 3c, upper inset image). After pressing the crossed junction at 0.6 GPa, the $I_{ds}$-$V_g$ trace gave the transitional transconductance peak between $V_g = -12$ and $-4$ V (Figure 3c, black trace), which can be reversibly erased by a $V_{ds}$ scan from 0 to 10 V at $V_g = -20$ V (Figure 3c, blue trace). We then cut the cCNT by moving the AFM tip fast perpendicularly cross the cCNT at the middle point with a pressure of 1 GPa, leaving only approximately 3 µm in contact with the sCNT. The friction force between the cCNT and the substrate helps the cutting operation and ensures that the crossed junction far away from the cutting point is not affected as evidenced by the unchanged shape and position of the other loosen end of the cCNT (Figure 3c, lower inset image). A slight shift of the $I_{ds}$-$V_g$ trace was observed but the transitional peak between $V_g = -12$ and $-4$ V overlapped with the original trace very well (Figure 3c, red trace). Further reducing the length of the cCNT is difficult because the friction force would not be able to hold the crossed junction intact and the cCNT will shift relative to the sCNT. In such a case, the modulation of the transconductance will disappear. Nevertheless, what we have observed suggests that the sources governing the transconductance fluctuation are very likely to be localized in contrast to previous reports where the modulation of conductance is solely determined by the capacitance and, hence, the size of attached nanotube or nanoparticle.12-14

To summarize briefly, we can see that (1) the as-grown crossed CNT junctions formed during the CNT growth procedure at high temperature (1000 °C)19 have shown a transitional transconductance fluctuation before the device is depleted; (2) loosening the junction contact by shifting the crossed CNT or removing it completely eliminates the transconductance modulation; (3) tightening the junction contact by pressing the crossing point could change the shape of the modulation, in other words, when the pressure intensity is above a threshold, a new peak can be created in the $I_{ds}$-$V_g$ trace; (4) the transitional transconductance modulation can be reversibly erased by applying a large $V_{ds}$ (>3 V) and recovered by pressing the junction above a threshold pressure (0.3 GPa); (5) no structural damage of the channel CNT is observed during all the manipulation and measurements as indicated by the unaffected $I_{ds}$-$V_{ds}$ traces; and (6) the transitional features is independent to the length of the crossed CNT, which suggests that the modulation effect is due to a localized interaction between the two CNTs.

As a control experiment, we tested using the same procedures a device that has only one semiconducting CNT between the source and drain electrodes with no crossed
CNTs. The diameter of the channel CNT is 3 nm, the same as that of the device in Figure 2. Pressing at the middle point of the CNT with a pressure \(>0.3 \text{ GPa}\) resulted in a significantly decreased conductance of the CNT but no significant modulation of transconductance in the subthreshold region (Supporting Information, Figure S2).

Local pressure can induce metallization of the semiconducting CNTs.\(^{11,20}\) However, the decrease of local band gap alone cannot explain the significant negative-to-positive transconductance transition, and it is clear from our data that the interaction between the two CNTs plays a critical role for the significant transconductance modulation. Therefore, we propose that the localized charges introduced by the deformation at the crossed junction can act as a local gate to generate the transconductance modulation.

First, as illustrated in Figure 4a, the mechanical deformation of the two CNTs can introduce localized states at the junction which are positively charged when \(V_g < 0\). These localized charges shift the effective gate potential that the sCNT “feels” so that the actual conductance is smaller than what is solely determined by the back gate. Note that the...
actual $l-V_g$ trace (red curve) is shifted to the left relative to the dashed red line, which labels the threshold determined by back gate alone. Second, as the $V_g$ ramps positively, the device becomes depleted fast and reaches the point where the potential barrier between the localized charges and the sCNT is small enough so that they start to discharge through a tunneling process. Now that the local gate effect at the junction starts to decrease, the $I_{ds}-V_g$ trace shows a turning point (Figure 4b). Third, the number of charges at the localized states keeps shrinking, leading to weaker and weaker local gating. The $I_{ds}-V_g$ trace gradually transits back to be fully controlled by the back gate, forming a plateau or peak (Figure 4c) before the final shutdown (Figure 4d). On the other hand, when the $V_g$ sweeps in the opposite direction starting from $V_g > 0$, the localized states first get recharged, which will result in a brief transitional step in the curve (Supporting Information, Figure S3). Subsequently the local gating will act simply as a constant shift of the threshold ($\Delta V_g$).

In conclusion, we have shown for the first time that the local deformation at the crossed CNT junction could introduce significant local gate effect under ambient environment and can be tuned by AFM manipulation. Such effect can be reversibly erased and recovered by applying a large source–drain voltage and by pressing at the junction above a threshold pressure, respectively. We propose that the gate effect is related to the localized charges residing at the deformed junctions, and the number of charges is estimated in the range of $10^2$ and $10^3$. The transconductance modulation in these crossed CNT devices have potential applications in electromechanical and memory devices, and the localized interaction suggests that many crossed junctions can be integrated along a single CNTFET. With the recent development of generating CNT crossbar networks directly during the chemical–vapor–deposition growth process,23,24 the localized states at the junctions could provide a promising way for designing scalable crossed CNT electronics.

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Supporting Information Available. Methods, additional references, and additional figures. This material is available free of charge via the Internet at http://pubs.acs.org.

REFERENCES AND NOTES


(18) The saturation current of all tested devices ranges from 20 to 35 \( \mu \)A. There could be more than one CNT as a bundle serving as the current channel. We have not identified the exact number of channel CNTs, however, all devices in our study showed similar behavior without inconsistency.


