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A Three-Terminal Carbon Nanorelay

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ABSTRACT

Three-terminal nanorelay structures were fabricated with multiwall carbon nanotubes (MWNTs). The nanotube relays were deflected by applying a gate voltage until contact (mechanical and/or electrical) was made with a drain electrode, thus closing the circuit. It was possible to achieve multiple switching cycles, showing that carbon nanotubes are suitable and practical systems for developing nanoelectromechanical devices of this kind.

Nanoelectromechanical systems (NEMS) are a rapidly growing area of research with considerable potential for future applications.[1] The basic idea underlying NEMS is the strong electromechanical coupling in devices on the nanometer scale in which the Coulomb forces associated with device operation are comparable with the chemical binding forces. Carbon nanotubes[2] are excellent candidates for NEMS devices. This is a consequence of their well-characterized chemical and physical structures, low mass and dimensions, exceptional directional stiffness, and range of electronic properties. Nanotube-based NEMS potentially have internal operating frequencies in the GHz range that make them suitable for a number of applications. (GHz frequencies are relevant for nanotubes with diameters of ca. 5 nm and lengths on the order of 100 nm.) Some prototype carbon nanotube-based NEMS have already been demonstrated, such as nanotweezers,[3,4] a random access memory,[5] and sensors.[6,7] Recently, a two-terminal carbon nanotube switch[8] and a three-terminal carbon nanotube relay[9,10] have been studied theoretically. The nanorelay was shown theoretically to act as a switch in the GHz regime and to be potentially suitable for applications such as logic devices, memory elements, pulse generators, and current or voltage amplifiers.[9] In this letter, we demonstrate the first fabrication of three-terminal carbon nanotube nanorelays and experimentally investigate the source−drain current as a function of applied gate voltage.

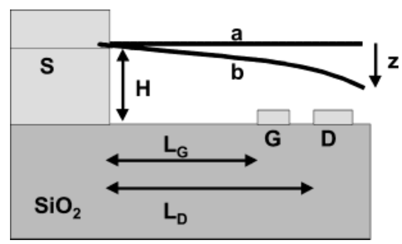

Figure 1. Schematic diagram of the carbon nanorelay device. The device consists of a multiwalled nanotube held by a source electrode (S) and suspended above gate (G) and drain (D) electrodes. $H = 150$ nm, $L_G = 1\ \mu$m, $L_D = 1.5\ \mu$m.

A schematic picture of the three-terminal device is shown in Figure 1. A conducting multiwalled nanotube is connected to a source electrode and suspended above the surface of a silicon chip, above gate and drain electrodes. Charge is induced in the suspended nanotube by applying a voltage to the gate electrode. The resulting capacitive force between the nanotube and the gate bends the tube and brings the tube end into electrical contact with the drain electrode.

The multiwalled carbon nanotubes used for our relay devices were synthesized by the plasma enhanced chemical vapor deposition (PECVD) method.[11,12] The length of the nanotubes was approximately 2−2.5 μm and the diameter spanned the range 20−100 nm. The method used for fabricating the three-terminal relay was similar to that reported recently for forming suspended single-walled nanotubes.[13] The height of the source electrode was designed to be higher (150 nm) than that of the gate and drain electrodes (15 nm). The electrode material was gold. To provide a support for the deposited nanotubes, PMMA was spin-coated

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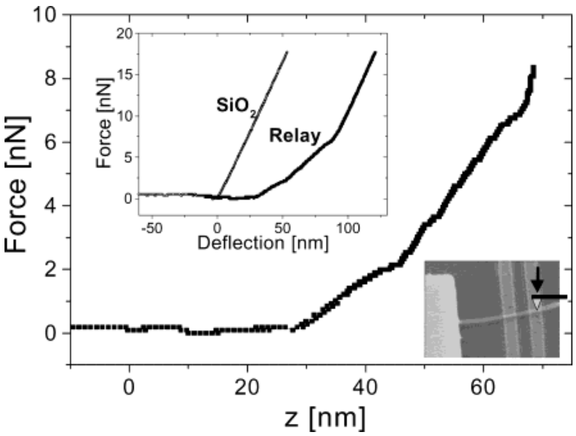

Figure 2. Force−distance measurement of relay structure. Upper inset: the force−distance measurement result for the nanotube relay and SiO_2 used as a reference for the tip deflection. Bottom inset: SEM picture and configuration for the force measurement.

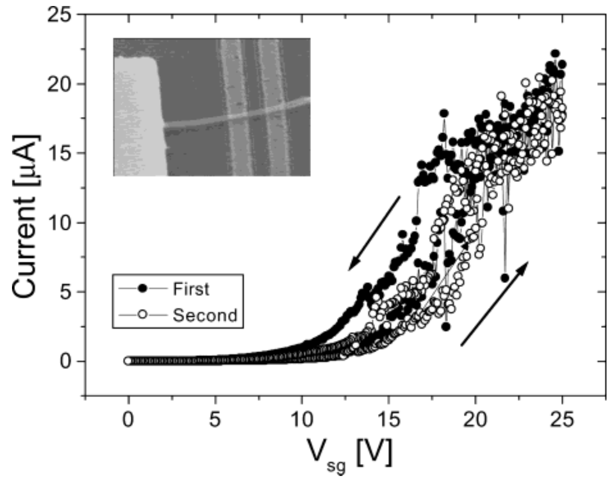

Figure 3. $I-V_{sg}$ characteristics of a nanotube relay initially suspended approximately 80 nm above the gate and drain electrodes. Current increased nonlinearly as the gate voltage increased (V_g < 20 V). Linear current increase and strong fluctuations are seen for V_{sg} > 20 V. The source−drain voltage, V_{sd}, was 0.5 V.

on top of the gate and drain electrodes and oxygen plasma ashed to be the same height as the source electrode. The multiwalled nanotubes were aligned and positioned with the ac-electrophoresis technique.[14] One droplet of well dispersed nanotubes in a sodium dodecyl sulfate aqueous solution was deposited and an ac voltage with 12 V peak-to-peak at a frequency of 13 MHz was applied for 10 s to attract the nanotubes to the source electrodes. Once the nanotubes were deposited, a top electrode (5 nm Ti plus 70 nm Au) was placed over the nanotube at the source to ensure good contact. The underlying PMMA substrate was then carefully removed to produce a nanotube suspended over the gate and drain electrodes. The separation between gate and drain was approximately 250 nm and the source drain distance was 1.5 μm. All measurements were carried out in air at room temperature.

Sixty-eight devices were fabricated, of which 38 remained suspended after the final processing step. Figure 2 shows the results of an AFM force−distance measurement carried out on one of the suspended structures in order to determine the mechanical pulling force needed to induce the nanotube to bend sufficiently to make physical contact with the substrate. This particular nanotube had a diameter of 50 nm and was 1.8 μm long.

The figure plots the force required to produce a given deflection of the suspended nanotube. As shown in the bottom inset, the AFM tip pushed the suspended nanotube at a point above the end of the drain electrode furthest from the source. Around 9 nN was necessary to bend the nanotube by 80 nm in order to reach the substrate. The upper inset shows the force−distance measurement on a larger scale and compares the relay measurement to that of the reference SiO_2 substrate. It can be clearly seen that after a deflection of 80 nm the nanotube deflection closely parallels that of the SiO_2 substrate, thus showing that physical contact has been made. The deflection was reversible showing that the nanotube did not permanently stick to the underlying electrode or substrate. The deflection cycle was repeated a number of times with just small shifts in the values, indicating that the nanotube did not always return to exactly the same starting position. The measured deflection of 80 nm is considerably less than the nominal distance between the suspended nanotube and the drain electrode (135 nm). It was found that most of the nanotubes were not suspended exactly horizontally but were suspended at an angle toward the substrate. The magnitude of the angle appears to depend on the length and the diameter of the nanotube. Longer and thinner nanotubes show a larger initial deflection from the horizontal. The prepared devices therefore have different initial distances between the nanotube and the drain, thus requiring varying amounts of deflection for contact and showing variations in the $I-V$ characteristics.

From the measured mechanical force, Figure 2, we can roughly estimate the gate voltage necessary for full deflection by estimating the relevant capacitances.[9] This gives a value on the order of some tens of volts.

The electromechanical properties of the nanotube relay were investigated by measuring the current−gate voltage ($I-V_{sg}$) characteristics, while applying a source-drain voltage of 0.5 V. The gate leakage current for these structures was measured to be 40 pA for V_{sg} = 30 V, and the leakage current of the electrodes without the presence of a nanotube was measured to be approximately 400 fA for the same V_{sg}. Figure 3 shows the $I-V_{sg}$ characteristics of one of the nanotube relays with an initial height difference between the CNT and drain electrode of approximately 80 nm. The drain current starts to increase nonlinearly when the gate voltage reaches 3 V (at this gate voltage the current is on the order of 10 nA). The nonlinear current increase is a signature of electron tunneling as the distance between the nanotube and the drain electrode is decreased. Beyond V_{sg} = 20 V there is a change in the rate of current increase, with it becoming more linear, and rather strong fluctuations can be seen. One possible explanation of the observations is that the nanotube comes into physical contact with an adsorbate layer on the electrode surface. In these measurements, the current does not become saturated, indicating that the nanotube does not have complete physical contact with the underlying electrode. The deflection is reversible. On reducing the gate voltage

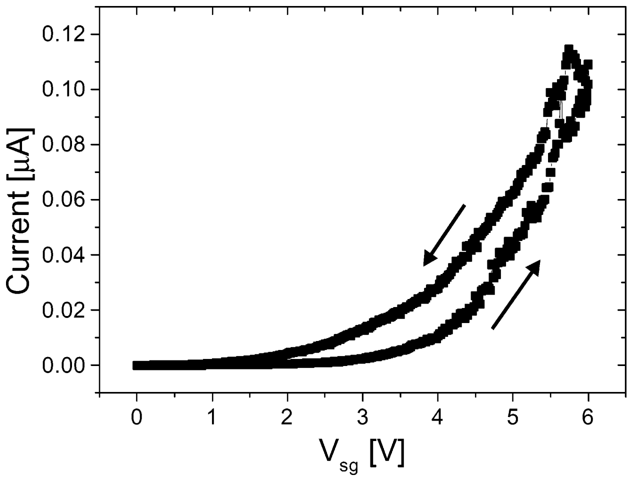

Figure 4. As Figure 3 but for another relay device and a more limited range of gate voltage.

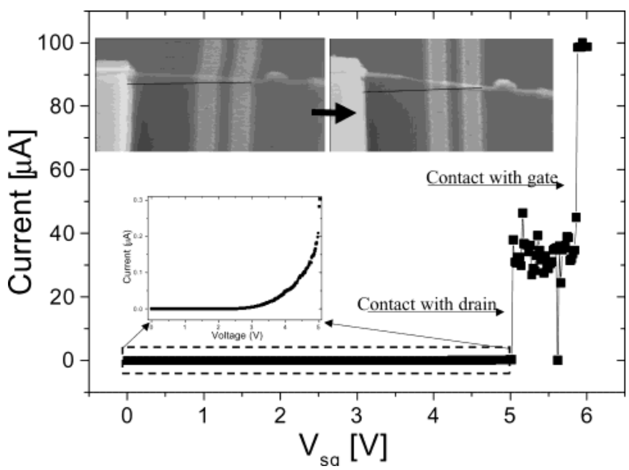

Figure 5. $I-V_{sg}$ characteristics of a nanotube initially suspended only slightly above the gate and drain electrodes. $V_{sd} = 0.5$ V. The nanotube makes contact with the drain electrode for a gate voltage of 5 V, leading to a rapid and striking increase in current. A second jump at a gate voltage of 6 V is due to the nanotube making physical contact with the gate electrode. Upper inset shows the SEM image of the relay before and after measurement.

the current decreases, showing some hysteresis, until it reaches zero for a gate voltage below ca. 3 V. The current measured during the increasing V_{sg} part of the second scan closely follows that of the first scan, especially in the region below $V_{sg} = 12$ V. There is a smaller hysteresis effect on the second scan.

Similar behavior can be observed for the other relay structures. Figure 4 shows the results of measurements on another relay. In this case the gate voltage was only increased to 6 V, and we did not observe the change to linear $I-V_{sg}$ behavior seen in Figure 3. The behavior of this relay is very similar to the previous one in this range of V_{sg}, although shifted slightly to lower gate voltages, indicating that the tube may have been initially closer to the substrate.

In the third example, Figure 5, we show a nanorelay that has made full physical contact with the drain electrode and has "stuck". The $I-V_{sg}$ behavior is qualitatively similar to the other two devices for a gate voltage below 5 V. As can be seen from the left-hand SEM picture, this nanotube was initially bent rather strongly toward the substrate. At a gate voltage of approximately 5 V the current rapidly increases to a value of 40 μA and stays at this value as the gate voltage is increased further. At this stage the nanotube has made full contact with the drain electrode. As the gate voltage is increased beyond ca. 6 V there is a second jump in current to beyond 100 μA (this was set as the compliance value of our measurement setup). At this point the nanotube has made contact with the gate electrode. This can also be seen in the right-hand SEM picture. For these measurements the deflection was not reversible and the nanotube remained attached to the gate and drain electrodes as the gate voltage was reduced.

The gate voltages required to make electrical contact are very close to those predicted theoretically.[9] This is at first sight rather surprising since the dimensions of our devices are approximately an order of magnitude larger than those used in the calculation. However, fortunately the effects of the larger dimensions cancel each other out to a large extent. The greater height, H, and nanotube diameter is compensated for by the greater length, L_G and poorer Young's modulus (0.7 TPa, based on the measurement in Figure 2) of the plasma-produced nanotubes used in our experiment. The calculations predicted a hysteresis as well as a strongly nonlinear increasing current at the required "pull-in" voltage. The hysteresis was found to be strongly dependent on the modeling parameters and was due to the appearance of two stable cantilever positions for certain combinations of design parameters and gate voltages, being mainly dependent on the surface forces.[9,10] The main qualitative difference between the theoretical predictions and these preliminary measurements is the more gradual switching-on of the current as the gate voltage is increased in the experimental data. This is presently the subject of further study. Work is also in progress concerning the resonant frequency and switching time of the devices. Since these structures are rather large we would expect the resonant frequency to be on the order of 0.1 GHz and thus approximately an order of magnitude lower than the theoretical estimates made for much smaller devices.[9] However, it should be possible to reduce the dimensions of the experimental devices. It is more difficult to estimate the switching time. Calculations have shown that this is likely to be strongly dependent on the details of the surface forces and phonon dissipation mechanisms[10] and will depend on the environment in which the measurements are made, but it is expected to be sub-ns. Measurements are in progress.

In summary, we have fabricated three-terminal carbon nanotube relay structures. By applying a gate voltage on the order of 5 V the nanotube was deflected, thus making electrical contact with a drain electrode. The theoretically predicted hysteresis effect was observed in the experiments, thus making these devices suitable as, for example, memory elements. Further properties such as the switching dynamics are presently being explored.

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