Enhancement of the transverse conductance in DNA nucleotides

Vincent Meunier$^a$ and Predrag S. Krstić
Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, Tennessee 37831, USA

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We theoretically study the electron transport properties of DNA nucleotides placed in the gap between two single-wall carbon nanotubes capped or terminated with H or N. We show that in the case of C-cap and H-termination the current at low electric bias is dominated by nonresonant tunneling, similarly to the cases of gold electrodes. In nitrogen-terminated nanotube electrodes, the nature of current is primarily quasiresonant tunneling and is increased by several orders of magnitude. We discuss the consequence of our result on the possibility of recognition at the level of single molecule. © 2008 American Institute of Physics. [DOI: 10.1063/1.2835350]

The possibility of genome sequencing by measuring the transverse conductivity upon applied dc bias while a DNA strand is translocated through a nanogap or nanopore has recently been the subject of some debates in the theoretical considerations, as well as of significant experimental activities. The origin of the debate stems from the fact that the Fermi energy of gold electrodes at 0 K is rather far from the molecular eigenlevels of the DNA nucleotides. The electronic transport is therefore dominated by nonresonant tunneling, which is highly dependent on the difficult-to-control relative geometry between the molecule and electrodes, while it is weakly dependent on the electronic structure of the molecule. In addition, this geometry is influenced by aqueous and electrolytic environment, thermal phenomena, and the effects of the applied transverse as well as longitudinal (translocating) electric fields. With a low transverse voltage bias and picoampere and subpicoampere tunneling currents the main difficulty remains in the poor signal-to-noise ratio, weakening the predictive power of distinguishing various nucleotides, or detecting their presence. These uncertainties are the essence of the recent controversy in the literature. Higher bias is unacceptable in an actual device realization: besides other possible destructive and nonlinear effects, electric forces at the negatively charged backbone of the DNA move the molecule toward the anode, disabling the translocation.

In this letter, we propose a new two-terminal setup for molecular conductance measurements, based on the use of specially prepared carbon nanotube (CNT) electrodes, Fig. 1. This approach enables a large, quasiresonant enhancement of the current at low bias, with the possibility of removing drawbacks of previous setups. Up to now, conductance measurements have been typically performed using standard metallic probes, such as gold. Unfortunately when DNA segments are sandwiched between this type of usually large cross-section electrodes, the structural deformations at the interface between electrodes and the base pairs can cause unacceptable variations in the measured current. The interface sensitivity in quantum transport is not only limited to measuring the current across DNA, it is a universal effect that makes measurement in single molecule particularly difficult. For that reason, there is currently a strong interest in the development of experimental apparatus that will alleviate the difficulty of controlling the coupling between the elect-

FIG. 1. (Color) Configurations of the CNT leads and molecules for the calculation of electronic transmission. [(a) and (b)] Empty nanogap between carbon-capped and H-terminated CNTs. [(c)–(f)] Detailed structure of nanogap created between N-terminated CNT with nucleotides shown explicitly for adenine, cytosine, guanine, and thymine, respectively. In each case, the DNA bases include a sugar-phosphate group as explained in Ref. 1. The distance between the CNT tips was kept at 1.5 nm. In this figure, all lead layers of the extended molecule used in the calculation are shown. Nitrogen, carbon, hydrogen, oxygen, and phosphorus atoms are shown in yellow, blue, white, red, and gold, respectively.
trod.es and the molecules. One attractive idea is to develop a system where the coupling between the molecule and the electrodes is better localized, in such a way as to ensure higher reproducibility of measured current-voltage curves. For instance, advanced two-probe electric systems have been devised to measure geometrical and electronic properties of DNA and DNA derivatives. 10 Another report shows that single DNA chains can make it possible to apply relatively low trapping voltages for dielectrophoretic trapping of DNA molecules, in order to recently developed where a CNT was used as an electrode saturated edges, Figs. 1

Unfortunately, since we seek noncovalent bonding to allow satisfactory resolution along the strand could be achieved.23 24 Second, the presence of nitrogen atoms at the end cap leads to a shift in the energy level of localized states at the tip toward the Fermi level and to an overall increase of the density of states around the Fermi level.23,24 For those reasons, we have considered N-doped (5,5) nanotubes as potentially improved electrodes to measure increased currents through the DNA nucleotides in the nanogap, Figs. 1(c)–1(f).

Using density functional theory (DFT), we demonstrate that single-wall (metallic) CNTs, properly terminated, can favorably replace metal electrodes, supporting the transverse electron transport across the DNA. The explicit circuitry engineering of connecting the nanotube electrodes into an external battery is not considered here, as was not considered in previous works with metal electrodes.1–4 In actual devices, nanotubes will eventually need to be connected to metallic electrodes attached to an external battery. Band realignment and charge injection in the vicinity of that “external” junction, as well as other imperfections in the external circuitry have an effect on the magnitude of the direct current. However, nanotube leads are typically rather long (tens of nanometers) and screening takes place over a distance much shorter than the nanotube branch, supporting our assumption of the infinite leads. Therefore this effect does not depend on the nanotube chemical ending close to the DNA nucleotide. The different behaviors for different endings will therefore be preserved (though the amplitude of the current might be modified). From a different perspective, we note that the effect of nanotube junction to external electrodes will not be expressed in a conventional four point measurement since it eliminates the effect of that type of contacts. To illustrate the enhancement of the conductivity with N doping, we calculate electron transport for all four types of the DNA nucleotides [adenine (A), thymine (T), cytosine (C), and guanine (G)], with C-capped, and H and N nanotube terminations, in geometry shown in Fig. 1. All the results in this letter correspond to the Landauer approach,25 which establishes that the electron transmission probability, T, is proportional to the molecular electronic conductance. T includes the detailed, quantum mechanical description of the molecule and its interaction with the leads. Assuming nearly thermodynamic equilibrium and a small voltage drop V across the system (from 0 to 500 mV), the so-called linear-response, equilibrium regime is known to yield quantitative results compared to a full nonequilibrium approach where the Poisson’s equation is solved self-consistently.26 Within these assumptions, we describe the electronic structure of the system with the self-consistent DFT calculation for the ground state. All-electron DFT calculations were performed using the quantum chemistry package NWChem,27 with the 3-21G contracted Gaussian basis set.

All of our results presented in the paper have been carefully checked with three different exchange correlation functional, i.e., with local density approximation (LDA),28 generalized gradient approximation (GGA),29 and hybrid methods (B3LYP),30 remarkably all leading to qualitatively the same conclusions, in spite of possible weak coupling present here. The numerical results shown in this letter correspond to the GGA functional, motivated by the fact that
GGA is a good compromise for extended electronic systems and molecular systems.

We carefully chose subsystems containing a DNA nucleotide and a large part of the CNT electrodes, with the appropriate terminations. To describe the open boundary conditions appropriate for the leads, we used the Green’s function matching method in conjunction with the generalized tight-binding approach to compute the transmission function. The integral of $T(E, V)$ over the band energy $E$ determines the current response $I$ to the applied voltage $V$. The transmission function $T$ depends not only on the electronic structure of the nucleotide but also on a number of other factors, e.g., the strength of the coupling between the base and the leads, which is a function of the base-lead geometry. Specifically, $T$ is very sensitive to the energy matching of the asymptotic Bloch channels in the leads with the energy levels of the base, deformed (i.e., shifted and broadened) by the coupling with the leads and adapted to the chemical potential drop across the molecule, resulting from the applied bias. Our approach takes all of these effects into account at the DFT level.

Typical $I$-$V$ characteristics for various lead terminations are illustrated with the example of guanine in Fig. 2. The current response for the N-terminated leads is found to be two to six orders of magnitude larger than that obtained with C- and H-terminations in the whole range of the considered biases. It is important to note that the current in the N-case reaches nanoampere values at about 0.4 V, while it stays in subpicoampere, or picoampere range for C- and H-terminations, comparable to the values obtained using gold electrodes with similar electrode-nucleotide geometries. The obtained enhancement might lead to an increase in the signal-to-noise ratio in conductance measurement of the DNA nucleotides, if other sources of uncertainty are unchanged.

![Figure 2](image1.png)

**FIG. 2.** (Color online) Comparison of the $I$-$V$ characteristics of guanine with N-, C-, and H-terminated CNT leads.

<table>
<thead>
<tr>
<th>Bias (V)</th>
<th>A</th>
<th>G</th>
<th>C</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{N}/T_{C}$</td>
<td>0.1</td>
<td>6.3 (3)</td>
<td>1.4 (3)</td>
<td>7.0 (1)</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>1.1 (7)</td>
<td>8.8 (3)</td>
<td>4.1 (4)</td>
</tr>
<tr>
<td>$I_{N}/I_{H}$</td>
<td>0.1</td>
<td>1.8 (2)</td>
<td>1.1 (3)</td>
<td>6.1 (2)</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>2.0 (5)</td>
<td>1.3 (6)</td>
<td>2.7 (5)</td>
</tr>
</tbody>
</table>

**TABLE I.** Current enhancements for various CNT terminations and for four DNA nucleotide types, with 0.1 and 0.5 V transverse biases. The format $a(b)$ means $a \times 10^{b}$.

Strong enhancement of the low-electric bias response with N-termination is found for all DNA nucleotides, as illustrated for two voltages in Table I. The enhancement factors also increase orders of magnitude with increase of voltage from 0.1 to 0.5 V. All nucleotides have an enhancement factor to the H-terminated leads, $I_{N}/I_{H}$, ranging between $10^5$ and $10^6$ for higher of the considered voltages. This factor to the C-termination, $I_{N}/I_{C}$, is more varying, between $10^7$ for adenine, down to $10^3$ for guanine.

While the leads define the boundary conditions and supply the electrons around the Fermi energy $E_{F}$, the physical mechanisms of transport across the interlead gap mainly depend upon the electronic structure of the molecule placed in the gap, while its coupling to the leads defines the tunneling characteristics of the junction. The existence of the electronic states localized in the gap, energetically close to the Fermi energy, is of a decisive importance for the overall conductance. In absence of such states, the mechanism of electron transport is dominated at low biases by the nonresonant tunneling, causing a significant suppression of conductance. Figure 3 shows the eigenenergy spectra of the extended molecules of Fig. 1. The strong presence of states located mainly at nitrogen and oxygen atoms of a nucleotide, extending across the gap, is obvious for N-terminated leads, for all of the nucleotides. The fact that no such states are present close to $E_{F}$ in the case of the carbon- and hydrogen-terminations explains the large increase of current in nitrogen-terminated CNTs.

Our results can be further analyzed in terms of the improved coupling between the N-saturated edges of the nano-
tube with the heterocyclic compounds present at one end of each nucleotide, since they share chemical similarity. DNA bases can be classified into two types: Adenine and guanine are fused five- and six-membered heterocyclic compounds called purines, while cytosine and thymine are six-membered rings called pyrimidines. In the nanogap geometries used in the present work, G and A nucleotides share similar current profiles. This property is compatible with the chemical nature of the base. It follows that for all terminations these two molecules carry the largest current. C and T nucleotides yield a quite smaller current response. Again, this can be understood from the fact that C and T are pyrimidine compounds, i.e., they have a single nitrogen-carbon heterocyclic group which can account for a lower coupling than in the case of purine bases. This feature makes the N-terminated CNT an excellent sensor for the (A,G) and (C,T) groups of the DNA bases. The issue of distinguishability within each of these groups remains an open topic requiring further studies and improvements.

Future work is required to understand the extent to which the described current enhancement survives the refinement of the model systems toward more realistic representations of the DNA molecule in an aqueous and electrolytic environment, averaging over the range of possible conformations of DNA while translocating through the nanogap formed by the leads, and consideration of background Faraday currents, as well as other contributions to observed signal-to-noise ratios. The choice of N- C- and H-terminations of the CNT leads is guided by a possibility of matching with atomic constituents of the DNA. We showed that the presence of N establishes a natural connection with purine and pyrimidine groups. Remarkably, the obtained selective enhancement of the current response, following from transition from regime of nonresonant to the quasiresonant tunneling, is not only limited to the DNA-related molecules. The local chemistry at the tip of the electrodes has a dramatic effect on the coupling with the molecule and functionalized CNT ends offering interesting possibilities for molecular recognition using CNTs.

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