Ab initio study of DNA nucleotides sandwiched between Au(111) electrodes

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Abstract. Using first-principles calculations, we study the electronic properties of the four DNA nucleotides sandwiched between two Au(111) electrodes. The geometrical structure of the systems is a realistic model of the recently proposed devices for DNA sequencing. For these metal-molecule-metal systems, we calculate the total and local density of states (DOS, LDOS), and the metal-molecule charge transfers. Our results suggest that the qualitative differences between the four systems are sufficient to ensure the recognition of the DNA bases by the proposed device. Nevertheless, the full investigation of the quantitative features of the current-voltage curves is needed to decide if the practical use is possible.

1. Introduction
The determination of a patient’s DNA sequence can, in principle, reveal an increased risk to fall ill with a particular disease [1, 2] and helps to design ‘personalized medicine’ [3]. Moreover, statistical studies and comparison of genomes [4] of a large number of individuals are crucial for the analysis of mutations [5] and hereditary diseases, paving the way to preventive medicine [6]. DNA sequencing is currently still a vastly time-consuming and very expensive task [4], consisting of pre-processing steps, the actual sequencing using the Sanger method, and post-processing in the form of data analysis [7]. Recently a new approach that relies on functionalized nanopore-embedded electrodes to achieve an unambiguous distinction of the four nucleic acid bases in the DNA sequencing process was proposed. It consists of measuring the current-voltage (I-V) characteristics of each nucleotide. This represents a significant improvement over previously studied designs [8, 9] which cannot reliably distinguish all four bases of DNA.

We calculated the electronic and structural properties of Au-X-Au systems (here X = deoxyadenosine monophosphate (dAMP), thymidine MP (TMP), deoxyguanosine MP (dGMP), and deoxycytidine (dCMP), respectively) by using the density functional theory (DFT) code SIESTA [10]. SIESTA uses pseudopotentials and expands the wave functions of valence electrons by linear combinations of numerical atomic orbitals. We used a double-zeta polarized (DZP) basis set with an energy cutoff of 25 meV. We performed Gamma-point calculations, by using the generalized gradient approximation (GGA) for the exchange and correlation functional, as parameterized by Perdew, Burke and Ernzerhof [11]. We used periodic boundary conditions. The investigated geometries for the Au-X-Au systems were built as follows (see figure 1): the structure of the isolated DNA nucleotides and of the bulk Au, respectively, were first optimized. For the latter, the equilibrium lattice constant was found to be 4.17 Å in good agreement with the experimental value. The calculated value is used to set the dimension of our hexagonal
supercell for the Au(111) surface. To keep a minimum of about 10 Å between repeated images of the DNA nucleotides we adopted a 5×5 surface cell resulting in lattice constant of 14.77 Å. The length of the supercell in the Z direction was 27.62 Å. This value leads to a distance of 15.5 Å between the two gold surfaces. This value is a compromise resulting from which best accommodates all four nucleobases geometries (see n section two). The orientation and the distance of the molecule with respect to the surface were then optimized until the maximum force was less than 0.04 eV/Å.

We are aware that this is just a first approach to the realistic description of the experimental device. Additional studies are needed to understand the dependence of the electronic structure with respect to the distance between the two surfaces. These studies should provide also a qualitative description of the defects on the electrode’s surfaces (i.e. defects of the atomic layers may lead to different distances between the electrodes in different regions of the nanojunction). This work is in progress in our group.

2. Results
The minimum distances between the organic atoms and the metallic surface resulting after the relaxation are given in table 1. One can see that our geometrical model describes fairly good all the four systems. On one hand, we kept the same distance between the gold plates; this corresponds to a given geometry of the sequencing device. On the other hand, the organic molecule-metal surface distances are within the limits of 2.10 Å and 2.65 Å which ensures a reliable description of the metal-molecule interaction.

Table 1. Distances (in Å) between Au plates and DNA nucleotides after the relaxation. Top values correspond to distances between the Au electrod and the nucleobase. Bottom: distances between phosphatic moiety of the nucleotide and the metallic surface.

|        | dAMP | TMP | dGMP | dCMP |
|--------|------|-----|------|------|
| Top    | 2.329| 2.647| 2.148| 2.528|
| Bottom | 2.103| 2.244| 2.298| 2.181|

In order to give a qualitative description of the electronic transport across the Au-DNA-Au devices, we concentrated our investigations on three relevant physical properties: (i) total density of electronic states (DOS) (ii) localized density of states (LDOS) and (iii) charge transfer.

The DOS corresponding to the four nucleobases, as well as to their associate metal-molecule-metal systems are given in figure 2. To compare the DOS for the metallic surface with that of the free molecules we set the Fermi level ($E_F$) to zero for both the free gold surface and the Au-X-Au systems. Next, we set the same value of the Hartree potential in vacuum for the free molecule and the gold surface. By inspecting figure 2 we note that the DOS of the gold(111) at $E_F$ is relatively low. This may indicate a relatively low tunneling probability for electrons at the metal-molecule interface. The analysis of the DOS for the four nucleotides (free and in contact with the metallic surfaces) shows that for dGMP the largest DOS peak occurs at $E_F$. In addition we note that this peak is almost unchanged when the gold surface is present (i.e. the red and the black curves are almost identical). As a consequence, we expect a strong signature of the guanine when the device is connected to a bias voltage. In the case of TMP the HOMO is located at about -0.6 below $E_F$, which decrease the electric signal. Finally, for dAMP and dCMP an intermediate situation occurs. In these cases, HOMO orbitals are located around -0.25 eV below $E_F$, in the presence of Au electrodes.

In order to explore the properties of the states close to the Fermi level for the four metal-molecule-metal systems, we compute their LDOS, i.e. $\rho(r, E) = \sum_i |\psi_i(r)|^2 \delta(E_i - E)$, where $\psi_i$
Figure 1. Geometrical structure used in calculation (for the system Au−dAMP−Au; similar models were used for the other three systems). The distance between the Au surfaces was set constant for the four systems (15.5 Å).

Figure 2. Top (four panels): The DOS for dAMP, TMP, dGMP, dCMP free (black) and attached to Au(111) electrodes (red). Bottom: the DOS for the clean Au(111) surface.

denote the eigenstates of the system and \( E_i \) the corresponding eigenvalues. In general, although the LDOS does not fully determine the conductivity, the regions where the LDOS is depressed are expected to be barriers for electronic transmission, while large values of the LDOS indicate a high tunneling probability. Non-zero values of LDOS are equivalent with the presence of molecular orbitals with energies in the region under investigation. We compute the LDOS of the four systems, on an one volt range centered on \( E_F \). This corresponds to a total bias of up to 1 eV applied to the device. The results are given in figure 3. First we note that the LDOS is non-zero over the dGMP for both energy ranges under investigation. Second, dAMP has a non-zero LDOS for the energy range \((E_F - 0.5 \text{V}, E_F)\). For TMP and dCMP, LDOS is concentrated over different chemical residues in the molecule, which does not favour the recognition of the DNA bases by measuring the I-V characteristics of the devices. These results are consistent with the DOS analysis.

Figure 3. The LDOS integrated between Fermi level \((E_F)\) and \(E_F - 0.5 \text{V}\) (left panel) and \(E_F + 0.5 \text{V}\) (right panel), respectively, for the four nucleotides.

Finally, we investigated the charge transfer between each molecule and two gold surface. To this end, we computed the electronic density of the metal-molecule-metal device \((\rho_D)\), that of the gold surface \((\rho_{Au})\) and that of the molecule \((\rho_M)\), respectively. For the two later cases the
geometry of the system was derived from that of the relaxed full system. Next we computed
the electronic density associated with the charge transfer \( \Delta \rho = \rho_D - \rho_{Au} - \rho_M \). By artificially
dividing the cell with planes parallel with the gold surfaces (see figure 1) and integrating the
\( \Delta \rho \) quantity, we directly estimated the total amount of electric charge across the region where
the molecule is located. While this method does not provide any information on the chemical
behavior, it has the advantage to provide accurate physical data, since the electronic density
is accurately computed within DFT. Precisely, we computed the total positive and negative
charge transferred between the molecule and surface across the region where the DNA base is
located \((Z_1 - Z_2)\), and across the region where the phosphate moiety is located \((Z_2 - Z_3)\) (see
the location of the two planes defining the three regions of interest in figure 1). The results are
given in table 2. They clearly show that for all systems the phosphate moiety has the tendency
to lose electrons, while the DNA bases have a small tendency of accumulating electrons. The
strongest manifestation of this effect is present for TMP and dGMP. Its consequence will be the
assymetry of the I-V curve of the device, with respect to the bias polarization.

|       | dAMP | TMP  | dGMP | dCMP |
|-------|------|------|------|------|
| \(Z_1 - Z_2\) | -0.04/0.46 | -0.06/0.59 | -0.10/0.48 | -0.02/0.45 |
| \(Z_2 - Z_3\) | -0.55/0.03 | -0.68/0.05 | -0.62/0.04 | -0.55/0.03 |

3. Conclusion
We studied the electronic properties of the DNA nucleotides (dAMP, TMP, dGMP, dCMP)
sandwiched between Au(111) electrodes, using a DFT approach. By analyzing the total DOS,
the LDOS and the charge transfer between the DNA nucleotides and the gold plates we found
that the proposed device is suited for the recognition of guanine and adenine. The asymmetry
of the I-V characteristics with respect to the bias polarization may lead to a distinct signature
for TMP unit also. To conclude, the qualitative analysis presented in this paper suggests that
the experimental setup based on our model can be used for DNA sequencing. Nevertheless, this
analysis does not give any indication on the magnitude of the total current for each nucleobase.
Further work is needed to decide if current values are large enough for practical applications.

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