Absence of dc-Conductivity in λ-DNA

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The electrical conductivity of biomaterials on a molecular scale is of fundamental interest in the life sciences. We perform first principles electronic structure calculations, which clearly indicate that λ-DNA chains should present large resistance values. We also present two direct procedures to measure electrical currents through DNA molecules adsorbed on mica. The lower limit for the resistivity is $10^6\ \Omega \cdot \mathrm{cm}$, in agreement with our calculations. We also show that low energy electron bombardment induces a rapid contamination and dramatically affects the measured conductivity, thus providing an explanation to recent reports of high DNA conductivity.

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Molecular devices are the final horizon in the miniaturization of electronic technology. The electrical transport properties of molecules are expected to differ dramatically from those of macroscopic conductors [1], and finding ways to measure these properties at such a small scale is an important challenge of the emerging nanoscience. In particular, DNA is a well-known molecule that appears as a promising molecular-wire candidate, which has been actively studied in the last few years [2–4]. Many of the efforts have a biochemical motivation, since understanding electronic transport through DNA is essential to characterize and control important life processes, such as radiation damage and repair [5,6]. However, the physical character of the problem of electronic transport through nanowires, and its importance for nanotechnology, has also motivated the study of DNA conductivity from a physical point of view [4,7,8]. In spite of its importance, the simple question of whether DNA is an electric conductor or not remains unsettled because of the complexity of the system and the difficulty of making clean-cut experiments. Recently, two outstanding works have been published, reporting very different transport properties. Fink and Schönenberger (FS) [9] find a linear *I-V* characteristic, with resistivities $\rho \approx 10^{-4}\ \Omega \cdot \mathrm{cm}$ for λ-DNA (random sequence) molecules 1 μm long. Porath and co-workers [10] report *I-V* characteristics with a clear gap of about 2 V and resistances of 3 GΩ at 4 V, for 10 nm long free standing poly(*G*)-poly(*C*) DNA chains ($\rho \approx 10\ \Omega \cdot \mathrm{cm}$).

This qualitative discrepancy is especially frustrating because it is not even theoretically clear whether DNA should conduct or not. This ignorance is justified by the complexity of the problem, and by the fact that the molecular environment is determinant and difficult to control. Many different aspects such as the sequence variability, and the effects of counterions and thermal vibrations, can influence the electron transport in different ways. Transport models have been put forward where charge is carried by polarons [11], solitons [12], electrons, or holes [5]. However, crucial quantitative information about the electronic structure is still missing. We have resorted to first principles calculations to obtain it.

Density-functional-theory (DFT) calculations for large systems are now feasible thanks to recent developments in linear scaling algorithms, with which the computational cost scales linearly with the number of atoms in the system N, instead of as N^3. We have used the numerical-atomic-orbital method [13–15] of linear scaling DFT, in the SIESTA implementation. We used the generalized gradients approximation for exchange and correlation [16], norm-conserving pseudopotentials [17,18], and a basis set of numerical-atomic orbitals. Their finite range [15,19] was chosen as in Ref. [14], with tests performed for ranges 30% longer. The atoms involved in hydrogen bridges have orbitals of long range. A double-ζ basis is used for all atoms except for phosphorous and for the atoms involved in hydrogen bridges, for which the basis contains extra polarization orbitals. The linear scaling computations were done using Wannier confinement radii of 4–5 Å. Further technical details are as in Ref. [20], where the approximations have been explained and tested at length. This method has already been used with success in a variety of inorganic systems [21] and biomolecules [14,22,23]. In particular, a thorough study has been performed on up to 30 nitrogenated base pairs [20], obtaining a very satisfactory accuracy in both geometries and interaction energies.

The calculations were done for a double helix of infinite length in acidic dry conditions. A unit cell with eleven base pairs (3.058 nm) and 715 atoms was repeated in the direction of the chain. The simplest sequence was first considered: polyguanine-polycytosine. The structure was

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completely relaxed, starting from an approximately known geometry [24] and following the atomic forces. This process required around 800 conjugate gradient steps. In the relaxed geometry, we performed a standard (order N^3) diagonalization of the Hamiltonian, to check the accuracy of the forces found by the order N method, and to obtain the Kohn-Sham eigenstates. The electronic structure close to the Fermi level shows well-defined minibands with eleven states per unit cell, one per basis pair. The topmost valence band has a bandwidth of 40 meV and is made of the π-like highest occupied molecular orbitals (HOMO) of the guanines. Their spacial distribution is shown in Fig. 1(a). Separated by an important band gap [25], the lowest conduction band has a width of 270 meV. It is made of the lowest unoccupied molecular orbitals (LUMO) of the cytosines, and it is shown in Fig. 1(b). These results may be of relevance for the experiments of Porath *et al.* [10] on repeated-sequence DNA, and they will be discussed elsewhere [27]. Notice that the wide band gap does not itself necessarily rule out electrical conduction, if there are enough hole carriers as a result of defects in the hydrogen atoms or counterions saturating the phosphates.

In order to address the situation for λ-DNA, we have performed a complete relaxation of a DNA chain analogous to the previous one, except for the swap of the guanine and cytosine bases in one of every eleven base pairs. The effect of the swap on the electronic structure of the chain is dramatic. The HOMO of the swapped guanine sinks 0.6 eV (15 times the HOMO bandwith) into lower valence band levels. This stabilization is due to charging effects, since guanines have an excess of electrons taken from cytosines. A guanine among cytosines is thus stabilized electrostatically. Figure 1(c) shows the analogous to 1(a) for the swapped structure, showing the cut in the HOMO-state channel, produced by the swapped pair. The situation is similar for the unoccupied band, albeit less dramatic. These results mean that, in terms of the one-dimensional Anderson model, the disorder fluctuations in λ-DNA, due to sequence variations, are substantially larger than the bandwidth, leading to electronic localization over very few base pairs and to an exponential decay of the conductance with length. This does not rule out residual conduction by hopping mechanisms (polaronic or not), although it should have a marked dependence on temperature and frequency [7].

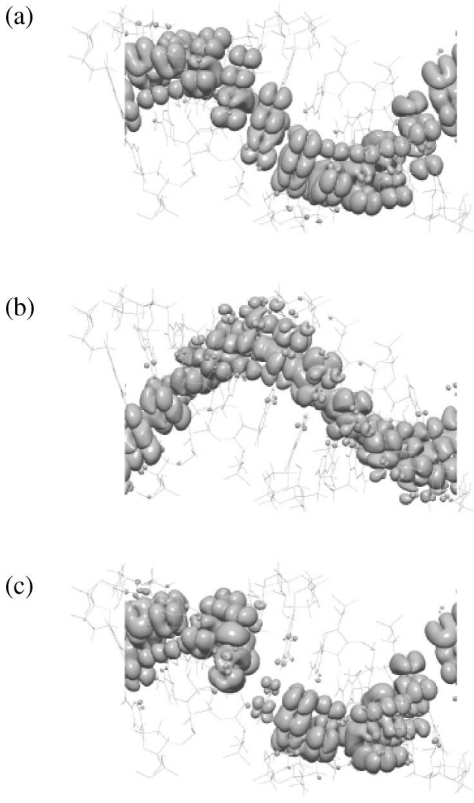

FIG. 1. Isosurfaces of constant density (5×10^{-4} e/a.u.^{3}) for (a) the eleven highest occupied states of poly(G)-poly(C); (b) the eleven lowest unoccupied states of the same; and (c) the eleven highest occupied states of the mutated DNA.

In order to verify our predictions, and to clarify the experimental situation, we have developed a simple and reliable technique [28] that allows measuring conductivity through long chain molecules. In the present work we apply this technique to study DNA conductivity. The λ-DNA sample was prepared as in Refs. [29,30]. The sample is then inspected by scanning force microscopy (SFM) to check the quality and surface density of DNA molecules. The SFM images show randomly distributed DNA chains 1.8 μm long, in good agreement with the selected DNA length. After deposition of the DNA, a region of mica 4 μm wide was left bare between two thermally evaporated Au electrodes, using a thin-wire shadow masking technique [31]. We have carefully checked that, during the whole evaporation process, the temperature never exceeds 310 K on the surface of the sample. Since molecular strand dissociation occurs only above 345 K, we do not expect any substantial thermal effects on the DNA structure. The gold patches, separated by the bare mica region, are then grounded with silver paint. In order to carry out the conductivity experiments, silicon nitride cantilevers, metallized with 20 nm titanium plus 60 nm gold films, were used as a second electrode. This sample preparation procedure results in a reliable method for making almost perfect electrical contacts in long molecules such as DNA.

Figure 2 shows a noncontact SFM image taken on the left border of the mica channel. Several DNA molecules appear clearly on the image, partially buried by the gold film, ensuring a good electrical contact. In order to measure DNA resistivity, we start by selecting one of the molecules and reducing the scan size until the molecule is on the center of a 10 nm wide image. The scan is then stopped and the tip is carefully driven to mechanical contact by elongating the piezoelectric scanner, while recording the normal force. At a previously selected normal force threshold, the tip motion is stopped and a

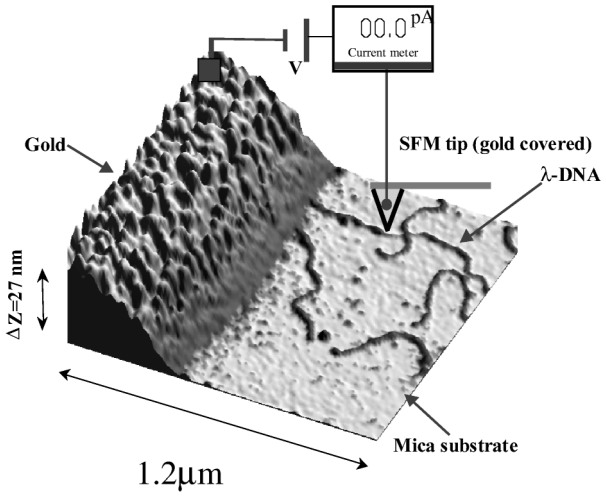

FIG. 2. Three-dimensional SFM image of the channel border, showing two DNA molecules in contact with the left gold electrode. The image size is 1.2 μm $\times$ 1.2 μm. We also present a scheme of the electrical circuit used to measure the DNA resistivity.

current-voltage (I-V) measurement is performed [32]. Thermal drift effects can be ruled out by taking an image immediately before and after each I-V measurement. The experiment is repeated at different distances to the border of the gold electrode, as well as at different force thresholds. The current sensitivity was 1 pA, and a bias voltage of up to 10 V was applied, without detecting any current. Therefore, we conclude that the resistance of the molecule was at least 10^{12} Ω, and that the minimum value for the DNA resistivity is $\rho \approx 10^4$ $\Omega \cdot$ cm. The same lower limit applied to every spot selected along the DNA molecule. In order to avoid any spurious current, we have limited the minimum horizontal distance between the conductive tip and the gold electrode to 70 nm. If the same I-V measurement is repeated on the gold electrodes, contact resistances of only about 30 Ω are obtained. A similar experiment performed with single wall nanotubes [31] gave resistances in the range $(0.5-10) \times 10^4$ Ω, depending on the selected nanotube. These low values prove the conductivity of our tips and the feasibility of making electrical contacts with a SFM tip to long molecules.

In order to improve the sensitivity of our measurement, we have carried out a second sample preparation by increasing the length of the DNA chains from 1 to 15 μm. Figure 3 shows a SFM image of the surface after preparation. From this image, we estimate that more than 1000 molecules connect both electrodes. With a bias voltage of up to 12 V between the gold electrodes, the measured current was below the noise level of 1 pA. Therefore, we calculate a minimum DNA resistance of 10^{16} Ω per molecule, and a minimum resistivity of 10^6 $\Omega \cdot$ cm. This result is consistent with previous work of Braun *et al.* [4]. Our result may still be consistent with those of Porath *et al.* [10], if we take into account

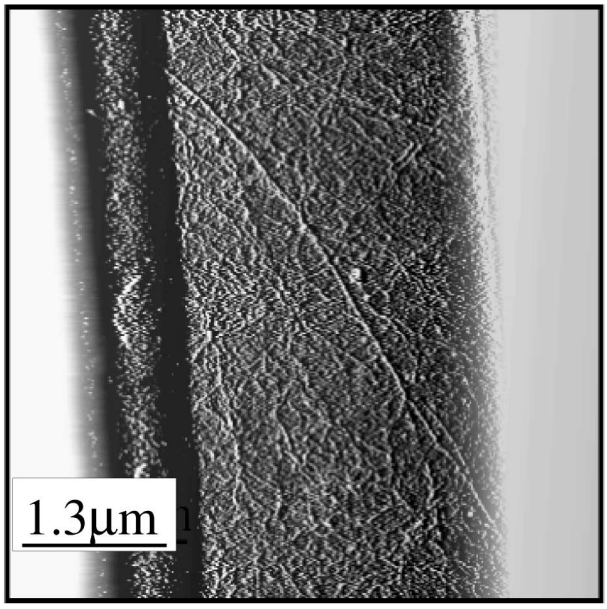

FIG. 3. λ-DNA strands connecting two gold electrodes spanned by a bare mica gap. By analyzing the image we conclude that at least 1000 DNA chains are connecting both electrodes. From the (absence of) current between both electrodes, a lower bound of 10^5 $\Omega \cdot$ cm per molecule is obtained for the resistivity of DNA at a bias voltage of 10 V.

our electronic structure obtained for poly(C)-poly(G). However, our resistivity is 10 orders of magnitude higher than that of FS [9].

Since both, experiments and calculations, strongly suggest that λ-DNA is an insulator, we should try to discuss the extremely low resistivity reported in Ref. [9]. We suspect that this value may be strongly affected by the method used by FS to visualize the DNA molecules, a low energy electron projection microscope [33]. Since the electron energy involved in this microscope is small (50–200 eV), FS assume that the sample is not affected by the electron beam. However, this is in contrast with a well-established fact in molecular biology: when biological tissue is irradiated with high energy particles, the secondary low energy (10–40 eV) electrons emitted along the track are the most harmful in inducing DNA damage [34]. In addition, at the base pressure reported by FS (10^{-7} mb), electron-induced hydrocarbon cracking may also be present. In order to address these problems, we have irradiated samples such as those of Fig. 3 with a low energy electron beam ($\approx$100 eV). After a dose of only 6500 C $\cdot$ m^{-2} (approximately 10 min at 10 A $\cdot$ m^{-2}), at a base pressure of 10^{-7} mb, the sample acquires metalliclike conductivity showing a clearly linear I-V characteristic, with a resistance of only 2×10^8 Ω. Further SFM inspection of the sample reveals that a contamination layer has been deposited on the surface and over the DNA, as a result of the electron bombardment. This shows that low energy electrons are not inert at all, and that special care must be taken to rule out their effects.

In summary, our first principles calculations indicate that the electrical conductivity of DNA should be strongly reduced by the sequence variability present in λ-DNA. In addition, two simple experimental techniques have been reported, which allow a clear visualization, and a direct measurement of the electrical transport through DNA and other long molecules adsorbed on a substrate. In agreement with the theoretical result, we have obtained an experimental lower bound of $10^6\ \Omega \cdot$ cm for the resistivity of λ-DNA, implying that it is a very good insulator. Finally, it has been shown that low energy electron bombardment can induce rapid contamination and affect dramatically the conductivity measurements.

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