MOLECULAR ELECTRONICS

A DNA that conducts

Experiments with conducting atomic force microscopy provide a clear demonstration of long-range charge transport in G-quadruplex DNA molecules, and allow a hopping transport model to be developed that could also be applied to other conductive polymers.

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Around 15 years ago, the idea of exploiting the self-repairing, self-organizing and self-reproduction properties of DNA to create nanoelectronic circuits was a dream of many researchers in the nanoscience community^{1,2}. The vision triggered research activities all over the world^{3,4}, but such devices never emerged. In fact, it proved difficult to deliver the most basic requirement: a reliable determination of the charge conduction capabilities of DNA over distances of at least several nanometres. As a result, the majority of researchers gave up, and, in the last decade, reports about successful charge transport

in DNA have become sparse. Writing in *Nature Nanotechnology*, Alexander Kotlyar, Danny Porath and colleagues now provide a comprehensive study of one particular type of DNA molecule, and show that it can deliver reproducible long-range charge transport⁵. The results could revive interest in the field of DNA electronics and also spur development in polymer-based nanoelectronics more generally.

Natural DNA consists of pairs of bases — guanine (G) and cytosine (C), and thymine (T) and adenosine (A) — that are stacked up to form a double-stranded helical structure. From theoretical and experimental studies, it is known that the

charge conduction path in the molecule is formed by the electronic wavefunctions that extend perpendicular to the base planes and overlap with those of the neighbouring planes, forming what is known as a π -orbital system^{1–4}. The overlap of the π orbitals depends sensitively on the relative orientation of the base planes and thus on the DNA structure⁶. However, the structure of DNA is extremely fragile and can undergo changes in response to its electrochemical environment and its interaction with an underlying substrate⁷. Such structural changes can alter the electronic properties of double-stranded DNA from a good conductor to an

insulator. This means that it is difficult to control the structure and properties of the molecule in a device geometry — that is, with the molecule deposited on a substrate and contacted to electrodes — and is one of the principal reasons why DNA electronics has floundered.

These structural issues are, however, not the only problem faced by DNA electronics. Native DNA, with its complex sequence, has an inherent disorder that hampers the formation of an extended wavefunction that could transport sizeable currents over sizeable distances. Furthermore, the injection of charge carriers into the π system, which is a crucial ingredient of the measurements, is difficult to control⁸. Finally, the design of any functional circuit from DNA will require at least a basic theoretical understanding of how carrier transport actually works in this complex biomolecule. In particular, a predictive model would need to be developed that can calculate the conduction behaviour of the system starting from a small set of parameters.

Porath and colleagues — who are based at institutes in Israel, the US, Italy, Cyprus, Spain and Denmark — have taken a major step towards addressing all these issues⁵. To overcome the undefined structure problem of double-stranded DNA, they replace the molecule with guanine-quadruplex (G4) DNA molecules⁹. These molecules feature quartets of G bases in a robust planar motif. The planar motifs are stacked on top of each other with a twist of roughly 30° from plane to plane, forming a stiff four-stranded helical structure (see close-up in Fig. 1). The choice of G4-DNA automatically solves the disorder problem because only one type of base is present. The G4-DNA structures can be found in nature at the edges of chromosomes in telomeric DNA⁹, but can also be created using the same methods that are used in double-stranded DNA synthesis and multiplication.

The researchers address the charge injection problem by making intentionally asymmetric contacts to the molecule: one end is contacted by a thick metallic layer, the other with a conductive tip of an atomic force microscope (AFM; Fig. 1). This approach allows images of the device to be recorded with almost atomic resolution, and for the effective wire length in the electrical transport measurements to be systematically varied. With the set-up, currents of more than 100 pA are measured in the molecule, and over a distance of roughly 100 nm. Furthermore, an unusual length dependence of the conductance is observed as is a threshold-like behaviour in

Figure 1 | Transport measurements of single G4-DNA molecules. The molecules (blue spirals) are first spread over an insulating mica substrate (grey). Next, a planar gold electrode is deposited that makes electrical contact to some of the molecules. The conductive tip of an AFM can then be used to electrically contact individual molecules with variable contact strengths. The charge transport is measured by connecting the AFM cantilever and the gold electrode to a voltage source and measuring the current. Close up: Artistic impression of the AFM tip forming an electrically conductive contact to the electronic system (light blue) of the G4 molecule (blue, red, black; simplified atomic arrangement).

the current-voltage characteristics, which has an asymmetry that depends on the coupling strength between the AFM tip and the molecule. Although some of these observations have been made before with G4 (ref. 10) and other DNA¹¹ molecules, the controlled and systematic study of Porath and colleagues now provides a clear-cut picture of charge transport in G4-DNA.

The picture provided by the experiments allows Porath and colleagues to develop a transport model that can quantitatively describe the current-voltage characteristics, as well as the length dependence using a limited set of parameters. The researchers reasoned that the intramolecular charge transport and the coupling to the electrodes are equally important, because both govern the energy landscape of the electrical circuit, and the non-trivial coupling to the AFM tip is accounted for by a bias-dependent parameter. The model shows that transport in the molecules involves thermally activated hopping from one multi-tetrad subsection of the DNA to the next, which is a similar mechanism to what is typically found in conductive polymers.

The model developed by Porath and colleagues is not specific to G4-DNA

and could be adapted to various different types of conductive polymer — this is probably the most important finding in the work for the nanoelectronics community. The results should also encourage researchers to revisit earlier experimental findings under the light of this model, and could therefore help lead to the development of new polymer-based cost-effective nanoelectronics. □

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