Self-assembly of nanoelectronic components and circuits using biological templates

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A multistep self-assembly process is proposed for the preparation of nanometer-scale electronics. The process is based on the assembly of a DNA network that serves, in turn, as a template for the subsequent assembly of functional elements using different levels of molecular recognition ability. Inter-element connectivity and connection to the "macroscopic world" is achieved by instilling electrical functionality to the DNA network. The feasibility of this approach was demonstrated by the DNA-templated self-assembly of a 12 μm long, ca. 1000 Å wide, conductive silver wire connecting two macroscopic electrodes.

Since the early days of microelectronics, a major effort has been devoted to the miniaturization of components and circuitry. As a result, the minimal feature size on a commercial chip has decreased gradually from about 10 μm in the early 1970s to ca. 0.18 μm at present. A comprehensive study by the *American Semiconductor Industry Association* (SIA) predicts a further gradual decrease in feature size to about 0.07 μm in 2010 [1] (Fig. 1). It is widely accepted that at these dimensions conventional semiconductor microelectronics will approach its useful miniaturization limits due to some fundamental limitations of large-scale photolithography and the expected failure of semiconductor physics in nanometer-scale components.

Nevertheless, even at these dimensions, the size of components on a chip will still be much larger than the size of the basic data storage component in biological systems such as in the DNA code, about 100 atoms with a volume of ca. 1000 $Å^3$.

The expected exhaustion of conventional microelectronics has focused considerable scientific and technological interest on two fundamental issues regarding future miniaturized nanoscale electronics: a) Operating principles of alternative, small size, electronic devices [2]. b) Alternative realization schemes for nanoscale electronic components and their integration into useful circuits [3].

In the last two decades, numerous suggestions have been made regarding the nature of the basic operating principles and components of nanometer-scale logic devices, ranging from all-optical and molecular-optical switch systems [4] to transistor-like switching devices based on charging effects (Coulomb blockade). Such single-electron charging effects were found in small grains [5] and molecules [6]. Room temperature operation of such transistor-like devices requires feature sizes in the range of 2–5 nm^3, about much smaller than the smallest commercial component expected from conventional microelectronics. However, progress in this field has been impeded by the lack of a simple approach to the integration of such basic building blocks into functional electronic devices, mainly due to the limitations of available physical manipulations, such as photolithography techniques, on the nanometer scale.

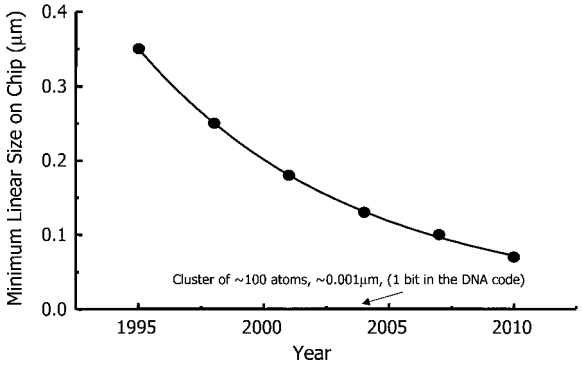

Fig. 1. The minimum linear size on a commercial chip as a function of time.

The expected failure of conventional physical processes at molecular scales presents the challenge of providing alternative schemes for the construction of useful electronic devices from nanometer-size and molecular building blocks. The major obstacles originate from the lack of appropriate tools for individual handling and manipulation of such small species, namely: a) positioning of molecular-scale components at molecularly accurate addresses, b) inducing inter-component wiring for establishing well-defined, functional electrical connectivity, c) establishing an effective interface between molecular-scale circuitry and the macroscopic world.

Due to obvious limitations in physically manipulating molecular size objects, it is widely accepted that electronic circuitry that is composed of nanometer- or molecular-size objects should be assembled from its building blocks using molecular recognition and self-assembly processes [7] rather than physical manipulations.

A major obstacle in implementing self-assembly processes for the construction of electrically functional elements lies in the fact that molecular recognition ability and electrical properties belong to two, probably mutually exclusive, classes of materials. On one hand, one can find metals and semiconductors as part of the inorganic world. Such materials display the desired electrical properties but possess only trivial molecular recognition ability, capable of forming only a few, rather trivial, lattices. On the other hand, organic-based materials exhibit poor electric properties; most of them are simply insulators. However, some

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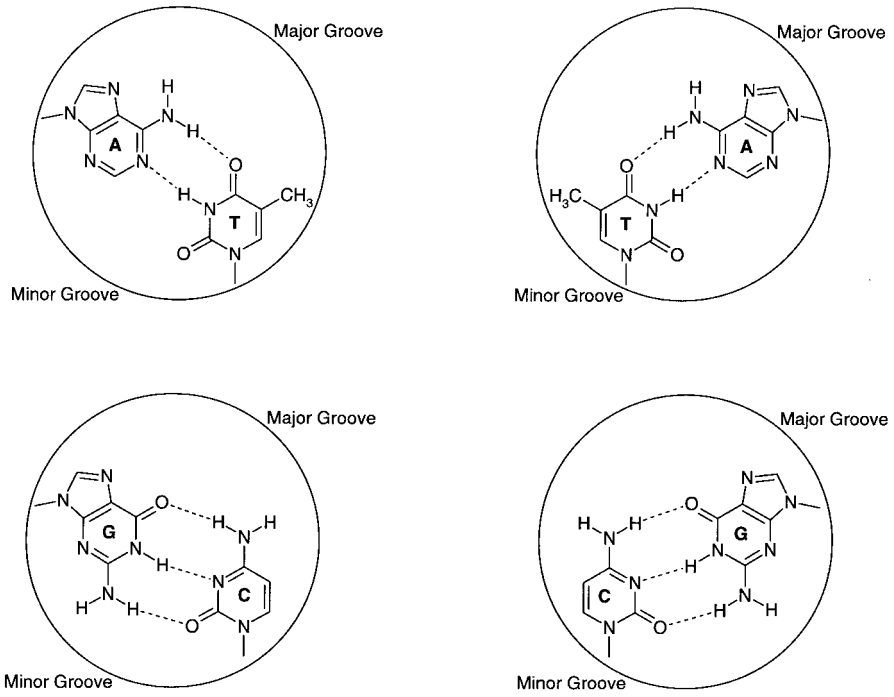


Fig. 2. Recognition groups in the major and minor grooves of DNA.

possess superb molecular recognition ability. For example, many biological molecules form highly complex, well-defined, extended supramolecular structures.

Therefore, a realistic solution to the production of functional circuitry by self-assembly should be the marriage or the sequential use of the two families of materials.

Since electrical functionality requires the utilization of conductive materials, of which metals and semiconductors are the prime choice, major attention should be devoted to the selection of the appropriate self-assembling systems that will allow the construction of highly complex structures. Recent progress in supramolecular chemistry offers better understanding and a limited structural control of supramolecular structures [3, 6]. Nevertheless, biological molecules still remain the prime choice for self-assembling species because of some of their unique properties: a) Many biological molecules are known to self-assemble and form highly complex supramolecular structures using highly effective and selective molecular recognition processes. b) Many biological self-assembly processes are coupled to mechanisms that are responsible for proof-reading during the buildup process. This allows error corrections prior to fixation of the supramolecular structure. c) Many biological recognition and assembly processes take place in well-shielded systems, allowing parallel processing of many different reactions in the same volume. d) Billions of years of evolution optimized an impressive arsenal of tools for handling biological molecules. Many of these tools are available nowadays for use in the construction of biological supramolecular structures.

An example of such a biological system that is capable of forming supramolecular structures from relatively simple building blocks is the DNA molecule. DNA is a linear polymer composed of four different building blocks, **A**, **T**, **C**, **G**. Base pairing between two sets of complementary bases **A**-**T** and **G**-**C** induces the dimerization of two complementary DNA strands to form a double helix structure. The base-pairs allow not only the construction of a highly accurate and well-defined structure but also the identification and binding of specific sequences along the DNA by other molecules. Many proteins, such as repressors, and artificial molecules are capable of recognizing a specific base-pair sequence along the DNA. Such molecules interact with the different proton donors and proton acceptors of the base-pairs that are exposed to solution at the major and minor groves (Fig. 2).

Here we propose a multi-step self-assembly process for the realization of miniaturized, electronically functional circuitry based on DNA molecules as building blocks for the supramolecular structure and on metals for the electronic functionality.

In a first step, a pre-designed network will be self-assembled from DNA molecules using their effective molecular recognition ability. In the following steps, the molecular network will be instilled with electronical functionality using different levels of molecular recognition ability of different electrically and electronically functional molecular and macromolecular species.

Figures 3–7 outline the proposed approach for the assembly of nanometer-size functional electronic circuits from molecular building blocks.

The first step involves the definition of macroscopic electrodes on an inert substrate. Since the electrodes are macroscopic, this process can be done using standard photolithographic techniques (Fig. 3).

The electrodes are provided with an identity by covering each one of them with a monolayer of a different short single-stranded oligonucleotide (Fig. 4). This step may

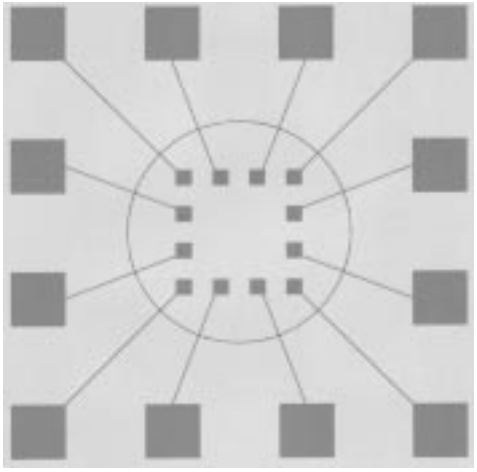


Fig. 3. Gold electrode array on inert substrate. Figures 4–7 concentrate on the contents of the circle.

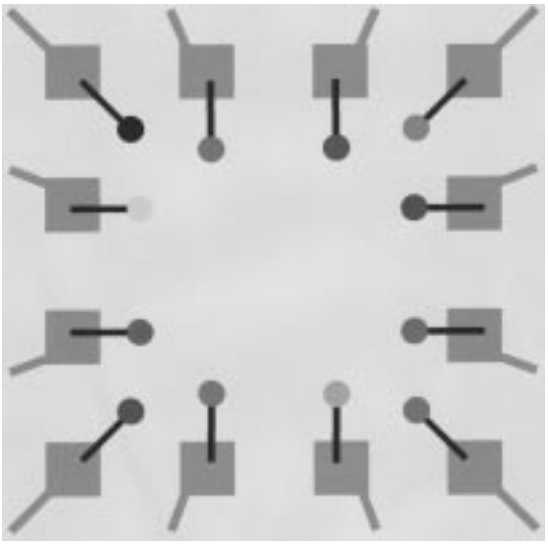


Fig. 4. Oligonucleotide monolayers on gold electrodes. The different grey circles represent different oligonucleotide sequences.

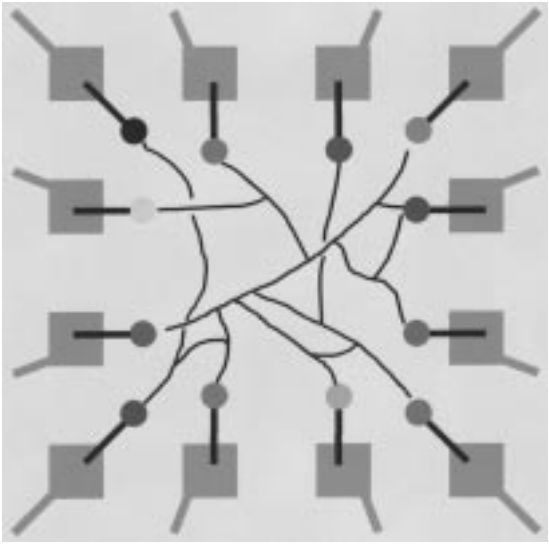


Fig. 5. DNA network bound to the oligonucleotides on the gold electrodes.

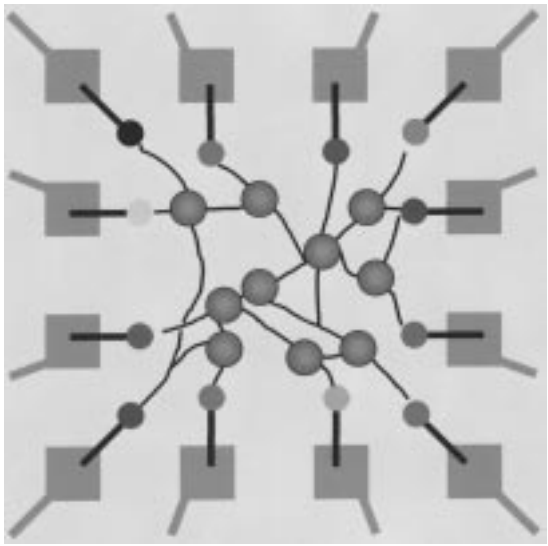


Fig. 6. Metal cluster–DNA binding agent systems bound to specific sequences on the DNA network.

still involve physical manipulations since the electrodes to be covered are macroscopic. After this step the electrodes are no longer identical since they bear a monolayer of oligonucleotides of a specific sequence and hence can recognize a specific complementary sequence in solution.

In the third step, the device is dipped into a solution containing DNA molecules having pre-designed sequences and sticky ends. The result of such a step should be the self-assembly of a DNA network having well-defined connectivity due to self-assembly processes between complementary DNA sequences [8]. Hybridization of DNA molecules with electrode-bound oligonucleotides ensures a pre-designed connectivity between the molecular-size DNA network and the "macroscopic world" (Fig. 5).

The previous steps provide the formerly addressless substrate with well-defined molecular addresses originating from the genetic code of the DNA molecules. This allows the subsequent positioning of functional electronic elements at molecularly accurate addresses using complexes that combine molecular recognition moieties capable of binding DNA molecules in a sequence-specific manner with molecular species that exhibit desired electronic properties, such as metal clusters [9] and grains [10] (Fig. 6). At the end of this step the network should bear the functional elements at pre-designed places on a network having the desired connectivity. However, since DNA molecules are expected to behave as insulators, the network is not functional. Therefore, the last step should be the functionalization of the DNA network in order to render it conductive.

Recently, we have demonstrated the ability to assemble the simplest electronically functional component, a conductive wire, using DNA templates [11] and the ability to allocate small metal grains at molecularly accurate addresses on the DNA skeleton [12], en route to the validation of the proposed concept.

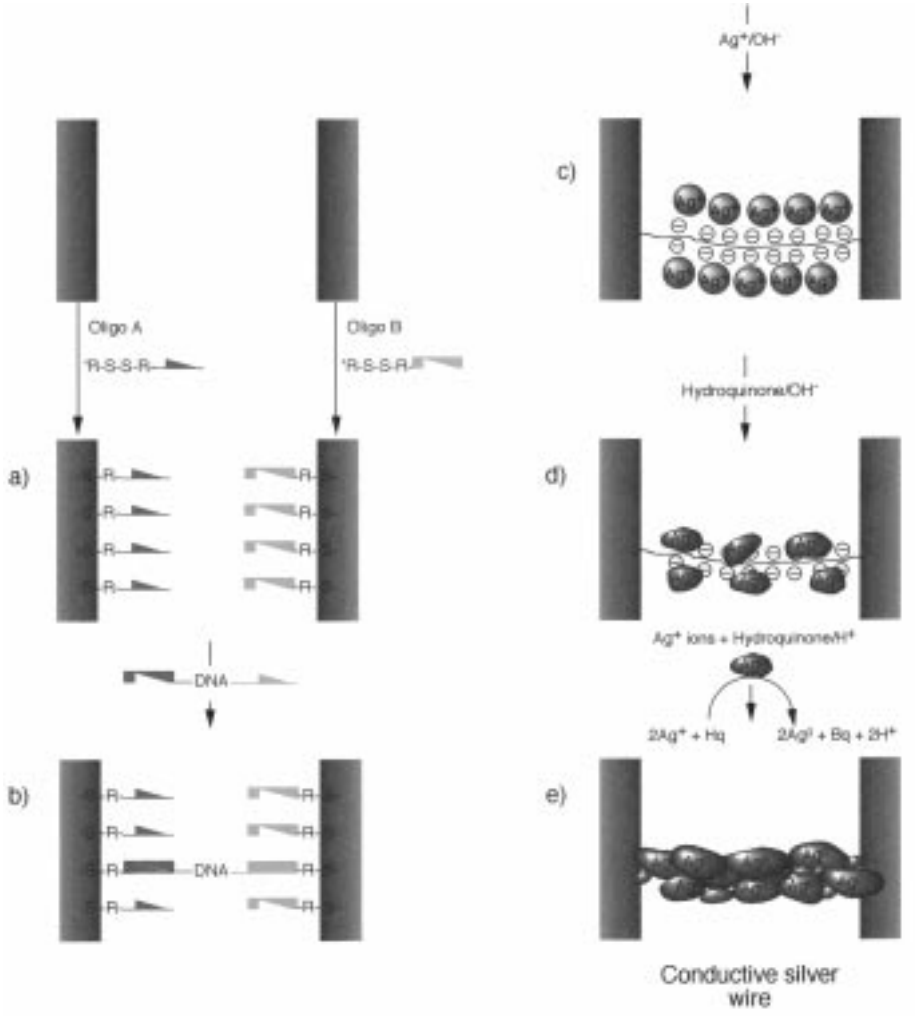
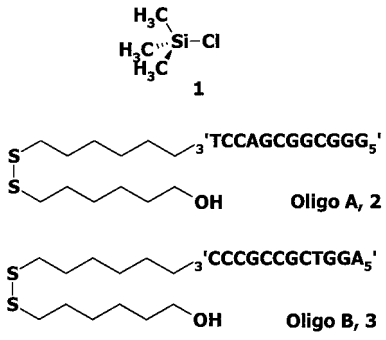


Fig. 7. A schematic diagram for a DNA-templated self-assembly of a conductive silver wire connecting two electrodes.

Figure 7 outlines the DNA-templated self-assembly of a conductive wire connecting two macroscopic electrodes. Two parallel gold electrodes, 12 μm apart, are deposited onto a glass substrate which was pre-treated with trimethylchlorosilane, **1**. In the next step, using a micropipette, one electrode is wet with a micrometer-size droplet of a solution containing the 12-base single-stranded oligonucleotide, **Oligo A**, **2**, bearing a disulfide group at its 3′ end. Similarly, the second electrode is covered with a solution containing the oligonucleotide **Oligo B**, **3**. ^{32}P labeling of the oligonucleotides reveals the lack of any measurable spurious adsorption of the oligonucleotides on the gold electrodes in the absence of the disulfide bridge. Thus, the oligonucleotides are bound to the gold surface through their disulfide bridge. In the next step, the electrode pair is covered with a solution containing λ-DNA, a ca. 16 μm long double-stranded DNA having two "sticky ends" that complement the oligonucleotides **Oligo A** and **Oligo B** that cover the electrodes. Molecules that have bonded to one electrode are stretched across the gap and hybridized with an oligonucleotide on the second electrode by applying flow normal to the electrodes or a retreating front of the aqueous droplet. Figure 8 depicts the process of attaching a DNA molecule to two gold electrodes (dark strips) using the method that utilizes the retreating front method. The exclusive attachment of the DNA molecule to the two gold electrodes could be demonstrated by its curving under solution flow normal to the electrode. Two-terminal I–V measurements that were performed on the dried sample show that a macroscopic DNA molecule is practically an insulator, having a resistance that is higher than the limits of our measuring devices, $10^{13}\ \Omega$ (for example, see inset in Fig. 10b).



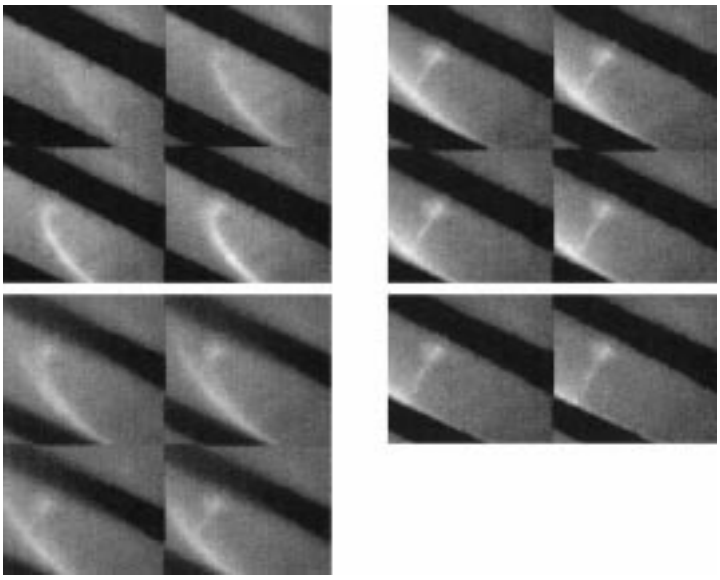
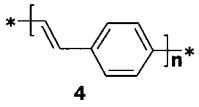


Fig. 8. Attachment of a DNA molecule to two gold electrodes via base pairing of its two sticky ends with surface bound oligonucleotides. The sequence starts at top left and ends at bottom right.

For the next steps, the DNA molecule is regarded as a polyanionic polymer. The metallization process is based on the localization of metal ions along the DNA molecule and their reduction to form a metallic wire.

First, the sodium ions on the DNA molecules are replaced by silver ions by simple ion exchange [13]. The formation of metal–nucleic base complexes [13, 14] increases the amount of silver ions that can be attached to the DNA. After the device has been rinsed, silver ions are localized exclusively along the DNA. The silver-loaded DNA is reduced using light or a basic hydroquinone solution to form metallic silver aggregates bound to the DNA by metal–polyelectrolyte interactions. The silver islands, bound to the DNA, are further "developed" in a process that is similar to latent image development in "black and white" photography using a solution containing silver ions and hydroquinone under acidic condition. In such solutions, homogeneous reduction of the silver ions by hydroquinone is very slow. However, it is accelerated in the presence of metal catalysts such as silver or gold. Therefore, under these experimental conditions, metal deposition occurs only on the silver metal grains that exist along the DNA molecule. The glass substrate remains practically clean of silver. The metal islands grow and merge to form a granular wire. Figures 9a and b depict the atomic force microscopy (AFM) picture of two fragments of the silver wire. The 12 μm long, ca. 1000 Å silver wire comprises 30–50 nm size metal grains deposited along the DNA skeleton. Using DNA networks, a network of silver wires as thin as 250–300 Å could be fabricated using by the same method. Two-terminal I–V measurements performed at room temperature on the silver wire attached to the two gold electrodes revealed that the silver wire is conductive (Figs. 10a, b). The I–V curves are nonlinear and asymmetric with respect to zero bias. The I–V curves are pseudo-linear at negative and positive bias, having a differential resistance of 1–30 MΩ, depending on the exact growth conditions of the wire. At lower bias, a zero current plateau of 0–10 V is developed, having a differential resistance higher than the limits of our measuring devices, 10^{13} Ω . The I–V curve is hysteretic and the exact shape of the curve depends on the last scan direction. The plateau could usually be eliminated by driving large currents through the wire, resulting in an ohmic behavior.

The use of DNA templates for the subsequent assembly of electronically active materials is not limited to metallic species. In another experiment, the self-assembly of an ultrathin poly(*p*-phenylene vinylene), PPV, **4**, connecting



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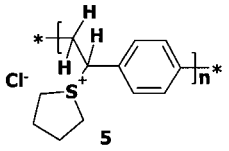
two electrodes was demonstrated (Fig. 11). Covering a device containing a DNA molecule attached to two gold electrodes with a solution of *pre*-PPV, **5**, results in an



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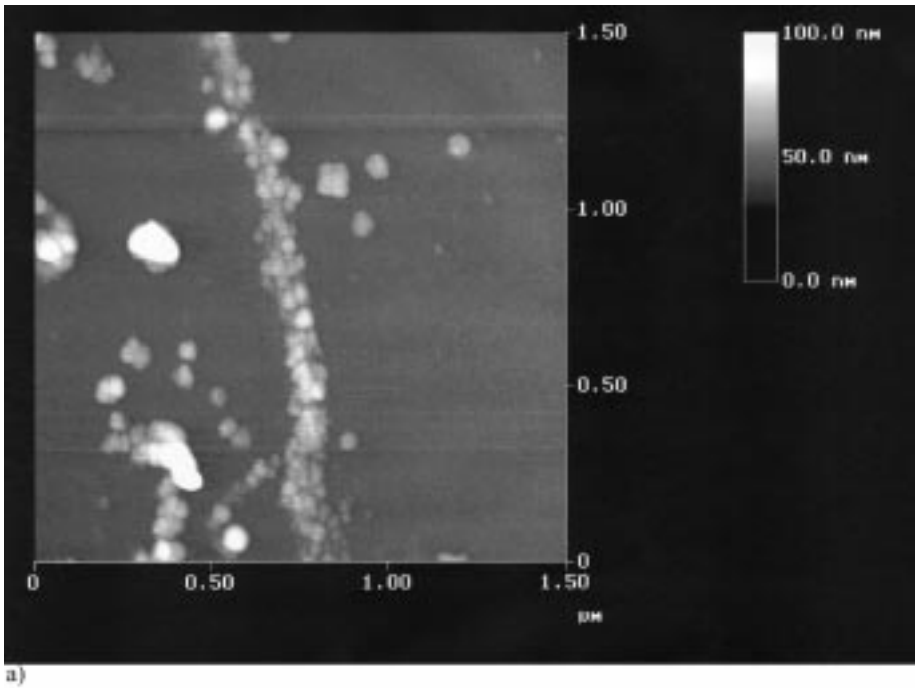
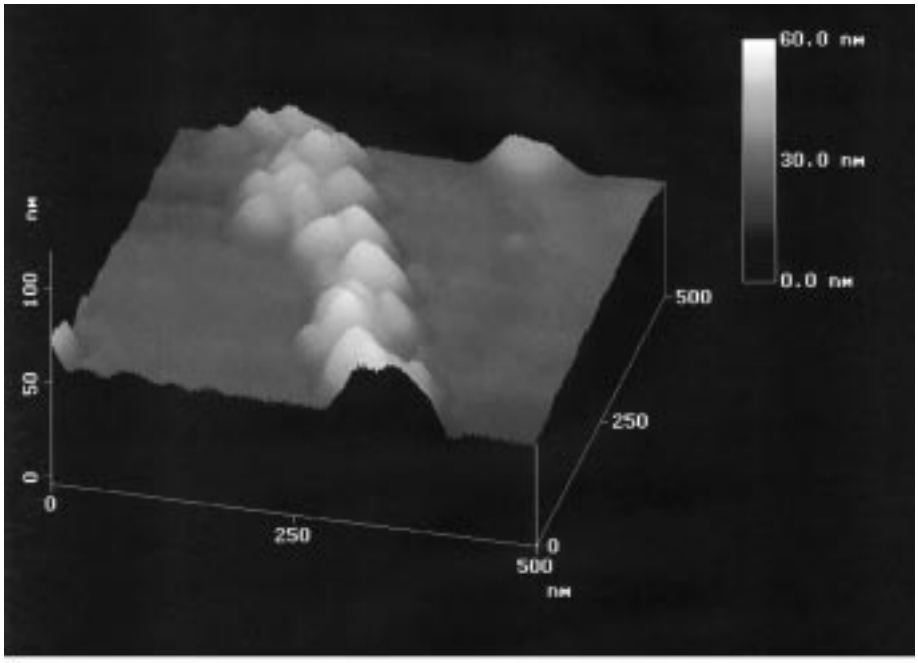
exchange of the sodium ions on the DNA by the positively charged *pre*-PPV polymer, **5**. Heating the device to 250 °C for 6 h gave a highly luminescent polymer wire exactly along the DNA molecule.

In summary, we have proposed a new, multi-step, approach for the self-assembly of nanoelectronic components and circuits using biological templates. The first step involves the assembly of a pre-designed network composed of organic-based molecules that are capable of



a)



b)

Fig. 9. Atomic force microscopy images of a silver wire connecting two electrodes 12 μm apart. a) 1.5 μm, b) 0.5 μm field size.

undergoing complex self-assembly processes through molecular recognition. In the following steps, the organic network is instilled with electric and electronic functionality by attaching to it different active components such as metal grains and clusters using different levels of molecular recognition processes. We have demonstrated the feasibility of this approach in the DNA-templated self-assembly of a conductive silver wire and in the self-assembly of an ultrathin photoluminescent PPV wire. Current efforts are focused on improving the properties and dimensions of the wires as well as on the assembly of functional elements such as transistors using the same approach.

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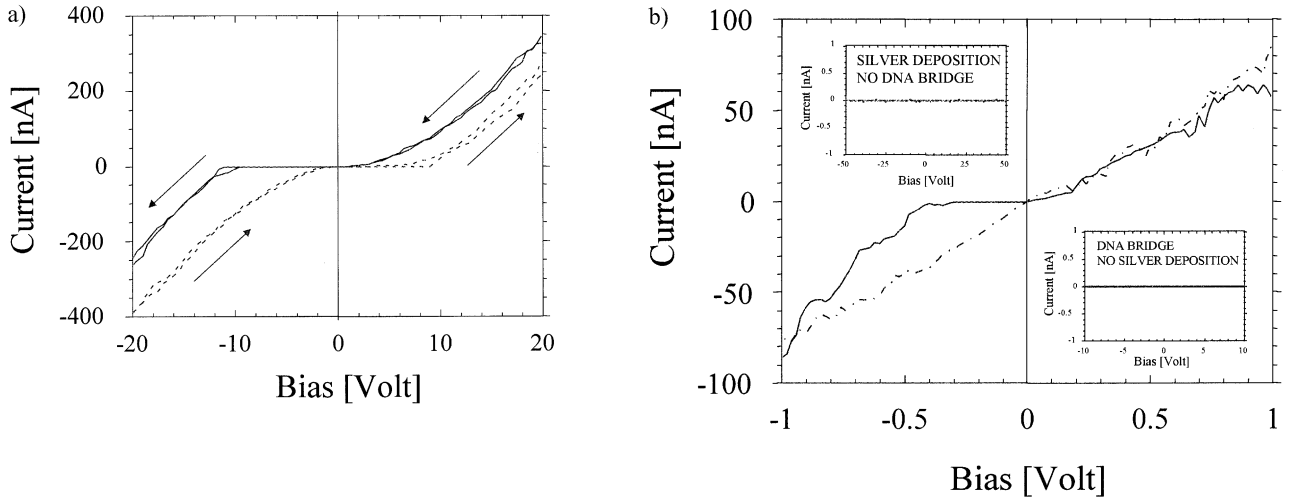

Fig. 10. a) Two-terminal $I-V$ curves of the silver wire depicted in Fig. 10. b) Two-terminal $I-V$ curves of a different silver wire in which the silver growth was more extensive. The plateau has been permanently eliminated (dashed line) by applying 50 V to the wire. Insets: The $I-V$ curves of a device that underwent silver deposition without a DNA template (top) and a device with a DNA bridge connecting the two electrodes (bottom).

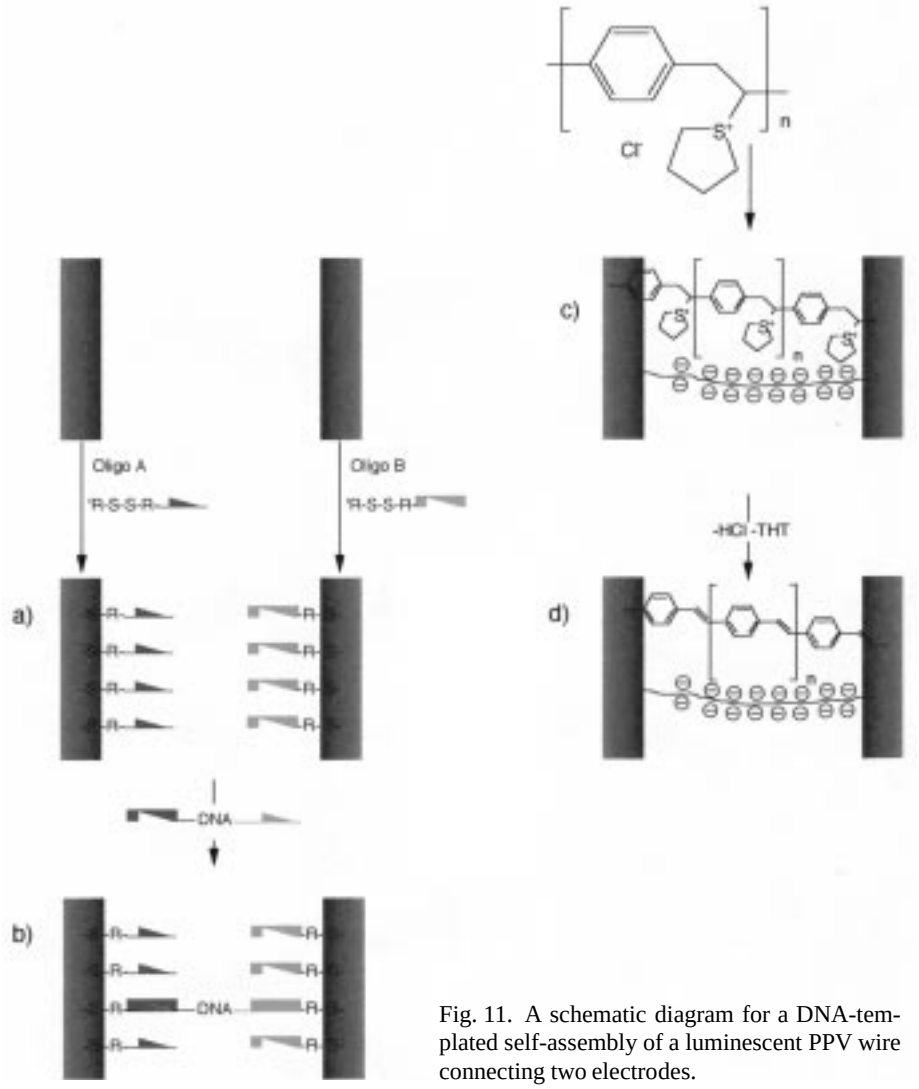

Fig. 11. A schematic diagram for a DNA-templated self-assembly of a luminescent PPV wire connecting two electrodes.

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