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On possibility of binary nanodevices production

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ABSTRACT

The work deals with possibilities of molecular level device production for use in binary data storage and in performing basic logical operations needed for binary data processing. Method of obtaining molecular logic gates through bottom-up production approach, that is, the method of transition from liquid state to solid state nanodevices, has been outlined. In addition, methods of obtaining some devices through combination of top-down and bottom-up production methods, that is the methods of building single nano particle transistors, have been depicted. The devices production justification has been considered through their characteristics such as the devices packing density, switching speed, device ease of addressing, device ease of production, and device concatenability.

Key words: *Molecular, Binary, Bottom-Up, Top-Down*

1. INTRODUCTION

Nanotechnology encompasses production and application of physical, chemical and biological systems at scales, ranging from individual atoms or molecules to submicron dimensions, as well as the integration of the resulting nanostructures into larger systems [1, 2].

The fabrication of conventional devices relies on the assembly of macroscopic building blocks with specific configurations. The shapes of these components are carved out of larger materials by exploiting physical methods. This top-down approach becomes increasingly challenging, however, as the dimensions of the target structures approach the nanoscale [3].

Nature builds nanostructured biomolecules relying on a highly modular approach [4]. The power of mechanic-chemical synthesis offers the opportunity of mimicking nature's modular approach to nanostructured materials [5]. Helical, tubular, interlocked, and highly branched nanostructures have been all prepared already exploiting this general strategy and the synergism of covalent and noncovalent bonds [6]. In fact, electroactive and photoactive molecules able to reproduce AND, NOT, and OR operations as well as simple combinational of these basic logic functions are already a reality [7, 8, 9].

Overall, these nanostructures transduce input stimulations into detectable outputs and, appropriately, are called molecular switches [10, 11]. The chemical transformations associated with these switching processes are often reversible. The chemical system returns to the original state when the input signal is turned off.

The interconverting states of a molecular switch can be isomers, an acid and its conjugated base, the oxidized and reduced forms of a redox active molecule, or even the complex and uncomplex forms of a receptor [7, 10, 11, 12]. The output of a molecular switch can be a chemical, electrical, and/or optical signal that varies in intensity with the inter-conversion process already [11].

2. MOLECULAR LOGIC GATES

The logic gates of conventional microprocessors are assembled interconnecting transistors, and their input and output signals are electrical [13].

Two decades ago, researchers proposed a viable strategy to execute logic operations at the molecular level [14]. The analogy between molecular switches and logic gates was recognized in a seminal article [15], in which it was demonstrated that AND, NOT, and OR operations can be reproduced with fluorescent molecules. For example, the anthracene derivative (Fig.1) is a molecular OR gate. It transduces two chemical inputs (concentrations of Na+ and K+) into an optical output (emission intensity), as is depicted in Fig.2. and Table 1. Changes in the

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concentrations of Na+ and/or K+ from low to high values switch the emission intensity from a low to a high value. The relationship between the chemical inputs and and the optical output translates into the truth table of an OR operation if a positive logic convention (low= logical 0, high= logical 1) is applied to all signals. The emission intensity is low (= logical 0) only when the concentration of Na+ and K+ are low (= logical 0). The emission intensity is high (= logical 1) for the other three input combinations.

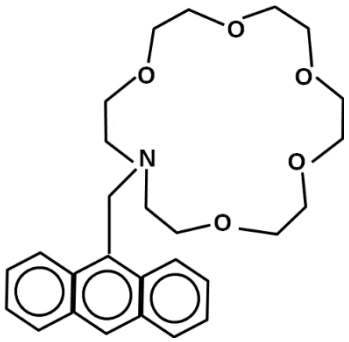

Fig. 1 *Scheme of anthracene derivative 2*

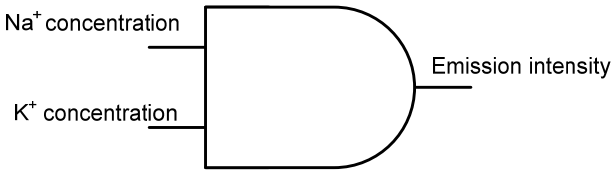

Fig. 2 *Anthracene derivative 2 as a logical OR gate*

Table 1 - Behaviour of anthracene derivative 2 as a molecular OR gate

INPUT 1 : Na^+ CONCENTRATION	*INPUT 2: K^+ CONCENTRATION*	*OUTPUT: EMISSION INTENSITY*
LOW= LOGICAL 0	*LOW= LOGICAL 0*	*LOW= LOGICAL 0*
LOW= LOGICAL 0	*HIGH= LOGICAL 1*	*HIGH= LOGICAL 1*
HIGH= LOGICAL 1	*LOW= LOGICAL 0*	*HIGH= LOGICAL 1*
HIGH= LOGICAL 1	*HIGH= LOGICAL 1*	*LOW= LOGICAL 0*

3. TRANSITION FROM FUNCTIONAL SOLUTIONS TO SOLID STATE DEVICES

The development of miniaturized molecule-based devices requires the identification of methods to transfer the switching mechanisms developed in solution to the solid state [16]. Borrowing designs and fabrication strategies from conventional electronics, researchers are starting to explore the integration of molecular components into functional circuits and devices [17, 19, 20, 27]. Generally, these strategies combine lithography and surface chemistry to assemble nanometer-thick organic films on the surfaces of microscaled or nanoscaled electrodes. Two main approaches for the deposition of organized molecular arrays on inorganic supports have emerged so far. In one instance, amphiphilic molecular building blocks are compressed into organized monolayers at air/water interfaces. The resulting films can be transferred on supporting solids employing the Langmuir–Blodgett technique [21]. Alternatively, certain molecules can be designed to adsorb spontaneously on the surfaces of compatible solids from liquid or vapor phases. The result is the self-assembly of oganic layers on inorganic supports [22].

For example, arrays of interconnected electrode/monolayer/electrode tunneling junctions can be assembled combining the Langmuir–Blodgett technique with electron beam evaporation [20]. Figure 7 illustrates a schematic representation of the resulting devices. Initially, parallel fingers are patterned on a silicon wafer with a silicon dioxide overlayer by electron beam evaporation. The bottom electrodes deposited on the support can be either aluminum wires covered by an aluminum oxide or n-doped silicon lines with silicon dioxide overlayers. Their widths are ≈ 6 or 7μm, respectively. The patterned silicon chip is immersed in the aqueous subphase of a Langmuir trough prior to monolayer formation. After the compression of electroactive amphiphiles at the air/water interface, the substrate is pulled out of the aqueous phase to encourage the transfer of the molecular layer on the parallel bottom electrodes as well as on the gaps between them. Then, a second set of electrodes orthogonal to the first is deposited through a mask by electron beam evaporation. They consist of a titanium underlayer plus an aluminum overlayer. Their thicknesses are ≈0.05 and 1μm, respectively, and their width is ≈10μm. In the final assembly, portions of the molecular layer become sandwiched between the bottom and top electrodes. The active areas of these electrode/monolayer/electrode junctions are ≈60–70 μm^2 and correspond to ≈106 molecules.

Note that only the portion of the monolayer sandwiched between the top and bottom electrodes is shown in Fig. 3.

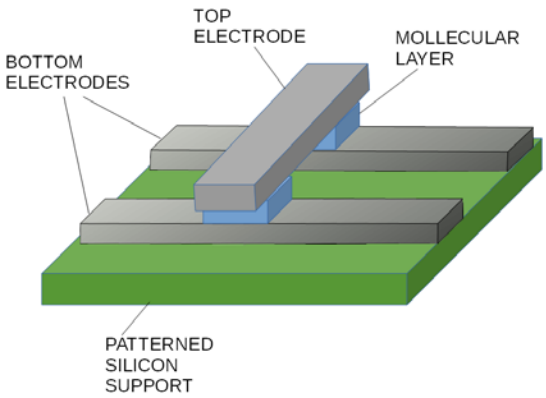

Fig. 3 *Interconnected electrode/monolayer/electrode tunneling junctions*

4. FABRICATION OF SINGLE NANO PARTICLES TRANSISTORS

A promising approach to unimolecular devices relies on the fabrication of nanometer-sized gaps in metallic features followed by the insertion of individual molecules between the terminals of the gap. This strategy permits the assembly of nanoscaled three-terminal devices equivalent to conventional transistors [23, 24, 25].
An example is illustrated in Fig.4 [23]. It incorporates a single molecule in the nanogap generated between two gold electrodes. The configuration is known as SET (single electron transistor), and represents special case of FET (field effect transistor. With SET electrons, one at a time, can tunnel from the first electrode to the second by hopping from one electrode to the small particle and then from the small particle to the second electrode. Initially electron beam lithography is used to pattern a gold wire on a doped silicon wafer covered by an insulating silicon dioxide layer. Then the gold feature is broken by electromigration to generate the nanogap. The lateral size of the separated electrodes is ≈100 nm and their thickness is ≈15 nm. Scanning electron microcopy indicates that the facing surfaces of the separated electrodes are not uniform and that tiny gaps between their protrusions are formed. Current/voltage measurements suggest that the size of the smallest nanogap is ≈1 nm. When the breakage of the gold feature is preceded by the deposition of a dilute toluene solution of C60, junctions with enhanced conduction are obtained. This particular molecule has a diameter of ≈0.7 nm and can insert in the nanogap facilitating the flow of electrons across the junction.

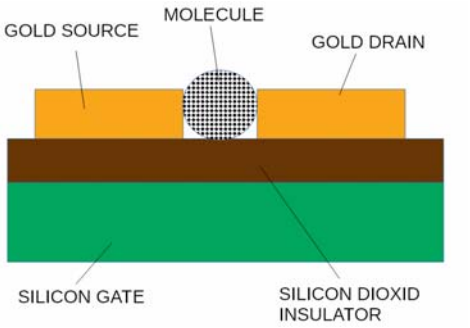

Fig. 4 *Single molecule based field effect transistor.*

Nanogaps between electrodes patterned on silicon/silicon dioxide supports can be bridged also by DNA double strands [26, 27]. The device in Fig. 5 has a 10.4 nm long poly(G)–poly(C) DNA oligomer suspended between two nanoelectrodes. It can be fabicated patterning a 30 nm wide slit in a silicon nitride overlayer covering a silicon/silicon dioxide support by electron beam evaporation. Underetching the silicon dioxide layer leaves a silicon nitride finger, which can be sputtered with a platinum layer and chopped to leave a nanogap of 8 nm. At this point, a microdroplet of a dilute solution of DNA is deposited on the device and a bias of 5 V is applied between the two electrodes. Electrostatic forces encourage the deposition of a single DNA wire on top of the nanogap. As soon as the nanowire is in position, current starts to flow across the junction. The current/voltage signature of the electrode/DNA/electrode junction shows currents below 1 pA at low voltage biases. Under these conditions, the DNA nanowire is an insulator. Above a certain voltage threshold, however, the nanowire becomes con-ducting and currents up to 100 nA can flow across the junction through a single nanowire. Assuming that direct tunneling from electrode to electrode is extremely unlikely for a relatively large gap of 8 nm, the intriguing current/voltage behavior has to be a consequence of the participation of the molecular states in the electron transport process.

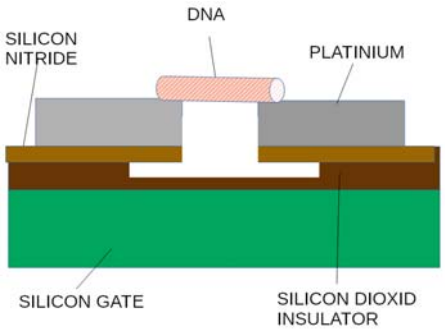

Fig. 5 *DNA based transistor.*

The device in Fig.6 is assembled patterning an aluminum finger on a silicon/silicon dioxide substrate by electron beam lithography [28].

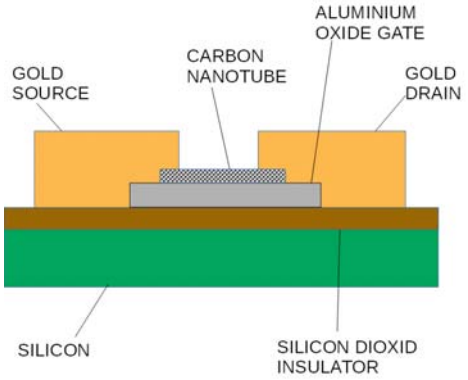

Fig. 6 *Carbon nano tube based field effect transistor*

After exposure to air, an insulating aluminum oxide layer forms on the aluminum finger. Then a dichloromethane suspension of single-wall carbon nanotubes is deposited on the resulting substrate. Atomic force microscopy can be used to select carbon nanotubes with a diameter of ≈1 nm positioned on the aluminum finger. After registering their coordinates relative to alignment markers, gold contacts can be evaporated on their ends by electron beam lithography. The final assembly is a nanoscaled three-terminal device equivalent to a conventional field effect transistor [13]. The two gold contacts are the source and drain terminals, while the underlying aluminum finger reproduces the function of the gate. At a source to drain bias of ≈−1.3V, the drain current jumps from ≈0 to ≈50 nA when the gate voltage is lowered from −1.0 to −1.3 V.

Thus moderate changes in the gate voltage vary significantly the current flowing through the nanotube-based device in analogy to a conventional enhancement mode p-type field effect transistor [13].
The nanoscaled transistor in Fig. 4 has a micro-scaled silicon gate that extends under the entire chip [23, 25]. The configuration in Fig. 6, instead, has nanoscaled aluminum gates for every single carbon nanotube transistor fabricated on the same support [28]. It follows that multiple nanoscaled transistors can be fabricated on the same chip and operated independently following this strategy. This unique feature offers the possibility of fabricating nanoscaled digital circuits by interconnecting the terminals of independent nanotube transistors.
The examples in Fig. 7 and 8 illustrate the configurations of nanoscaled NOT and NOR gates implemented using one or two nanotube transistors.

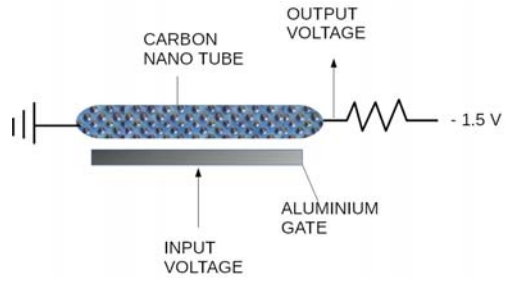

Fig.7 *Carbon nano tube based NOT gate*

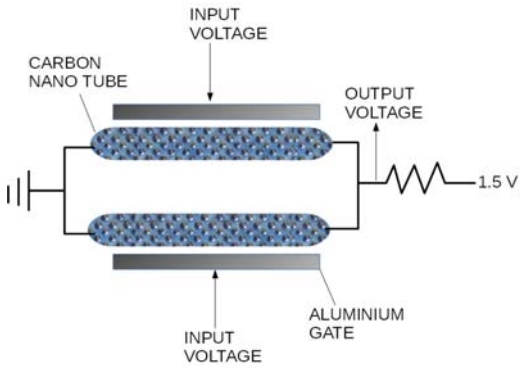

Fig.8 *Carbon nano tube based AND gate*

4. CONCLUSION

It would be interesting to use any of above mentioned devices only if they have specific advantages. These advantages should pertain to devices packing density, switching speed, device ease of addressing, device ease of production, and device concatenability. Generallyl the switching rate between the two states is low with liquid state molecular devices. They can perform complex logic operations at single molecule levels, but on the other hand they present very serious problems associated with addressing and concatenability [29]. Generally, with liquid state molecular devices, substantially smaller number of atoms are needed to store per bit of information. Most of the liquid state molecular switches for digital processing developed so far rely on bulk addressing, which means that relatively large collections of functional molecules are addressed simultaneously in solution.
One limitation of all SET devices is that they are individual transistors; and though it would be possible to fabricate many of them on the same substrate, this would mean that they all share a common gate electrode and would not be individually controllable [30]. A step toward carbon nanotube integrated circuits is the construction of circuits employing up to three carbon nanotube transistors, each with an independently controlled gate electrode. The nanotube transistors Are not SETs relying on Coulomb blockade but instead employ semiconducting carbon nanotubes to fabricate a traditional FET architecture but with a channel width of just one nanotube [30]. Building multiple CNT transistor circuits is a major step forward; but there is still one obstacle to cross before the achievement of true nanoscale devices, and that is to provide nanoscale interconnects between the active electronic components. The source, drain, and gate electrodes and the interconnects fabricated by top-down methods can all be made smaller, but the ultimate step would be to wire the interconnects using conducting carbon nanotubes. Ultimately,this would all have to be achieved with some method in mind for scaling up and automating the process. At the moment the circuits rely on maneuvering individual nanotubes by Atomic Force Microscope [30].

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