MOLECULAR ELECTRONICS: CURRENT STATE
AND FUTURE TRENDS

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The paper reviews the current state of molecular electronics and considers the most interesting trends in its development. It is noted that microscopic dimensions in quantum processes are not the only advantage of molecular technology. It is also important that chemical synthesis of molecular systems ensures the identity of assembled functional elements, thereby providing reliability and efficiency of quantum processes in molecular electronic devices. We propose using the quantum effect of the Peierls instability, which is readily realized in one-dimensional molecular systems. Advantages of this approach are discussed.

In microelectronics, considerable attention has been recently focused on a search for physical principles for the design of novel functional elements. As regards quick turn-on and miniaturization, the potentialities of classical semiconductor technology with its limited electron mobility, high heat release, and connection problems are already exhausted.

Further progress is associated with semiconductor devices utilizing quantum phenomena: the idea of a quantum transistor has been implemented in unique heterostructures. Numerous current theoretical and experimental studies have dealt with artificial low-dimensional structures: quantum films, wires, and points. Specific quantum phenomena observed in these structures are expected to provide a basis for a radically new class of electronic devices.

In recent years, along with practical attempts to construct a new type of electronic device, there has been a sharp increase of interest in so-called molecular electronics. Enthusiasts in this field believe that a novel computing device, characterized by a high degree of miniaturization, quick turn-on, and low heat release, could appear in the near future [1]. In this device, the basic processes of information recording, storing, and transmitting are expected to take place at a level of one molecule or molecular assembly of higher or lower degrees of complexity.

Since the pioneering works of Carter and Aviram [2, 3], molecular, or, more precisely, intramolecular electronics [4], developed on the basis of specific processes involving one molecule or molecular assembly. In particular, Carter [5] has proposed a brilliant idea of a "soliton switch" as a basic unit of a molecular computer. Unfortunately, implementation of this and other ideas is hampered by numerous difficulties, of which information input and output at a molecular or molecular assembly level are the hardest and most serious. Also of great concern is the problem of reliable operation of a unit molecular system, which, as many researchers suppose, can be solved by using optical methods of recording and reading [6]. This is precisely the area where definite progress has been made.

For example, a molecular gate [7] identical to a typical semiconductor gate has been worked out in the IBM Research Center of Molecular Electronics. It has two inputs (A and B) and one output (C) (Fig. 1). The inputs are represented by cyanine dye molecules conjugated with quinone molecules. The working molecule is porphyrin. The output is a chromophore molecule. The dimensions of this gate are more than 100 times smaller than those of the smallest theoretically possible semiconductor gate.

The molecular gate functions as follows. When a light beam of an appropriate frequency falls on one of the inputs (A or B), an electron is generated in the cyanine molecule. From cyanine this electron passes through quinone to porphyrin. The arrival of a single electron to the porphyrin molecule produces no effect. Two electrons from both inputs force the electron out to the chromophore molecule. The state of the latter can be identified with a laser.
The experts of the IBM company believe that all logical components of a computing device, namely, triggers, counters, and so on, can be developed from this molecular gate.

Nevertheless, with respect to miniaturization, reliability, and convenience for users, a molecular computer run by the electrical field is thought to be preferable. Unfortunately, advances in this direction are less visible, including the application of the tunnel effect. This effect underlies the functioning of a quantum transistor realized in semiconductor heterostructures (Fig. 3a) [8]. Carter [9] has proposed a hypothetical molecular system to be used as the basis of a molecular transistor. Although no such transistor has yet been developed, the proposed approach is of great importance and will undoubtedly play a definite role in the creation of a molecular computer (Fig. 3b).

A particularly interesting molecular system with field-controlled conductivity was suggested by Aviram [11]. This is a molecular electronic switch consisting of two perpendicular polyconjugate chains connected by a bridge (Fig. 2). It was readily synthesized by Tour [12]. This electronic switch is thought to run as follows. On application of an external electrical field perpendicular to the polyconjugate chains, an electron can transfer through the bridge from one chain to the other. The chain which contributes an electron becomes conducting. As the direction of the external electrical field changes, the conducting chain goes over to the dielectric state, and the other chain becomes conducting. As in the case of Carter's "soliton switch" [5], the problem of connection to the complex three-dimensional molecular system of Aviram–Tour remains unsolved.

Considering the current state of molecular electronics, we note that it is not molecular systems as such that should be brought into focus but, rather, the particular physical processes, apparently the quantum ones, underlying the functioning of these systems. The molecular level of these processes is favored not only because of the microscopic scale of these processes, but also because it predetermines a way of constructing molecular assemblies. Synthesis of molecular systems is just the first step in the self-assembly of molecular devices. This ensures an identity of assemblies and of their size, and thereby reliability of quantum processes and molecular devices. The use of molecular technology

Fig. 1. An IBM molecular gate [7]: 1) input A, 2) input B, 3) cyanine molecule, 4) quinone molecule, 5) porphyrin molecule, 6) chromophore molecule output C.

Fig. 2. Aviram–Tour's molecular electronic switch [11, 12].