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# A Brief Overview of Nanoelectronic Devices

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January 1998

MITRE
McLean, Virginia

To be presented at the
1998 Government Microelectronics Applications Conference (GOMAC98)
Arlington, VA, 13-16 March 1998

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**Sponsor** MITRE MSR Program
**Project No.** 51MSR89G
**Dept.** W062

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# A BRIEF OVERVIEW OF NANOELECTRONIC DEVICES

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## ABSTRACT

This paper surveys and explains nanometer-scale, quantum-effect alternatives to micron-scale, bulk-effect transistors in digital circuits. The status of R&D and recent important advances are reviewed briefly.

## I. INTRODUCTION

For the past forty years, electronic computers have grown more powerful as their basic sub-unit, the transistor, has shrunk. However, the laws of quantum mechanics, plus the limitations of materials and fabrication techniques soon are likely to inhibit further reduction in the minimum size of today's bulk-effect semiconductor transistors. Researchers have projected that as the overall size of the bulk-effect, semiconductor transistor is aggressively miniaturized to approximately 0.1 micron (i.e., 100 nanometers) and beyond, the devices may no longer function as well.

Thus, in order to continue the miniaturization of integrated circuits well into the next century, it is likely that present-day, micron-scale or microelectronic device designs will be replaced with new designs for devices that take advantage of the quantum mechanical effects that dominate on the much smaller, nanometer scale. (Note that 1 nanometer, abbreviated nm, is one billionth of a meter or 10 atomic diameters.)

This paper briefly surveys such quantum-effect, nanometer-scale alternatives to micron-scale, bulk-effect transistors for use in electronic digital circuits. Longer, in-depth reviews of this topic appear elsewhere [1-3].

The topic of nanoelectronic devices subdivides into two broad areas, as follows:

- Solid-state quantum-effect nanoelectronic devices
- Molecular electronic devices

The comments above are summarized and amplified in Figure 1, as well as in the sections of this paper that follow.

## II. SOLID-STATE QUANTUM-EFFECT NANOELECTRONIC DEVICES

Solid-state quantum-effect nanoelectronic devices are the nearer-term alternative for continuing to increase the density and speed of information processing. This technology, which changes the operating principles, but not the solid fabrication medium for integrated circuits, might extend Moore's Law of electronics miniaturization to produce devices down to 25 nm in length, beyond the domain of the bulk-effect transistor. Present-day field-effect transistors (FETs) on commercial integrated circuits are approximately 1 micron or 1000 nm across, and even the most optimistic proponents of aggressively miniaturized bulk-effect FETs predict that they will cease to function effectively when their gate lengths dip below 25 nm, which corresponds to an overall device length of approximately 100 nm.

By contrast, quantum-effect switching devices tend to function *better* when they are made smaller. Solid state quantum-effect nanoelectronic devices might be made as small as approximately 12 to 25 nanometers across and still function effectively if they could be fabricated reliably and uniformly on that scale. Presently, mass fabrication on this small scale does present a set of formidable challenges, no matter what the device design.

However, a number of solid-state nanoelectronic switching devices have been fabricated and demonstrated, and prototype solid-state nanoelectronic processors already are operational, as well [4,5]. Moreover, the drastic decrease in size that could result from the wide-scale introduction of such nanoelectronic devices might produce ultra-fast, low power integrated circuits with as many as 100 billion or even 1 trillion switching devices on a single CPU chip, as well as Terabyte nonevanescent memories on a chip.

Such great advances would require, however, the reliable, uniform mass fabrication of features only 5 to 10 nanometers wide in solids. This is at least twenty-five times as small as is achievable using UV lithography, the present industrial method of choice. More modest, near-term goals do not require such extreme precision, but take advantage of other very desirable properties of solid-state quantum-effect devices, such as low power consumption and high speed.

### A. Types of Solid-State Nanoelectronic Devices

As is indicated in Figure 1 and explained in greater detail elsewhere in the literature [1], there are 3 basic categories of solid-state nanoelectronic devices: (1) Quantum Dots (or "artificial atoms"), (2) Resonant Tunneling Devices, and (3) Single-Electron Transistors (SETs). A small "island" composed of semiconductor or metal in which electrons may be confined is the essential structural feature that all these quantum-effect, solid-state nanoelectronic devices have in common. The island in a nanoelectronic device assumes a role analogous to that of the channel that forms

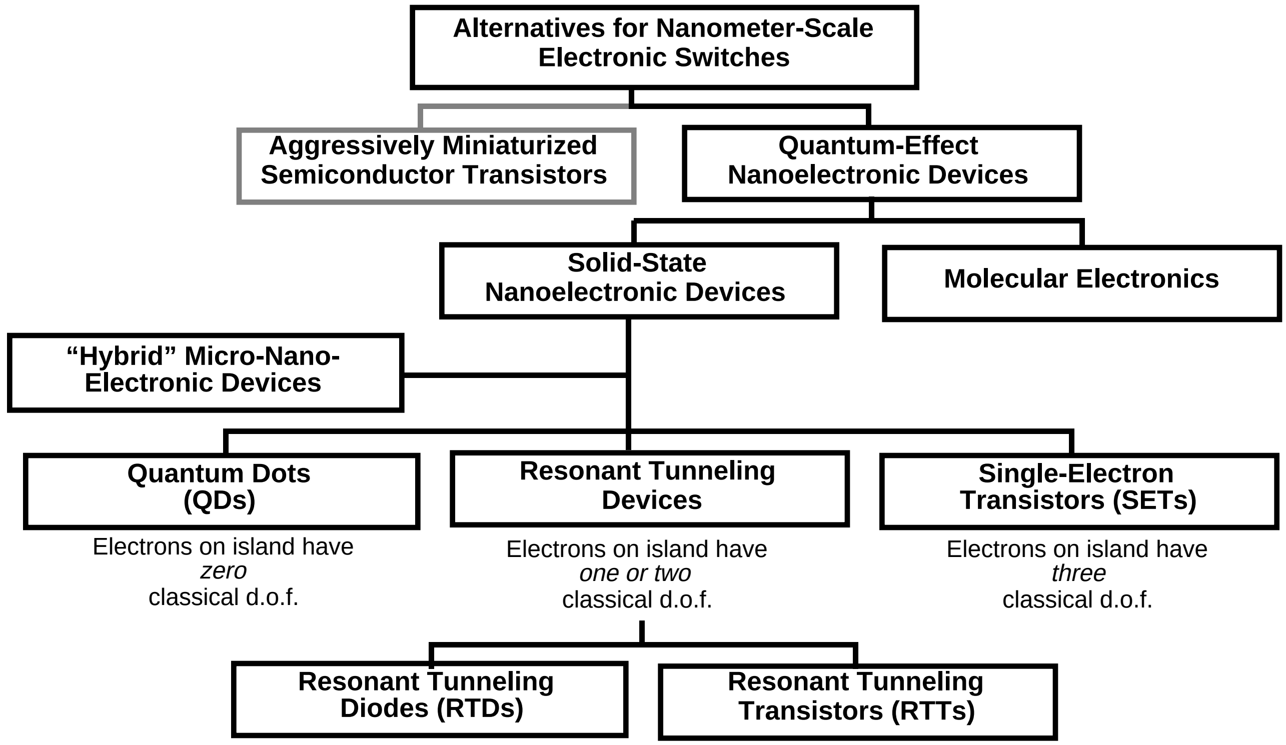


**Figure 1. Taxonomy of nanoelectronic devices**

beneath the gate in a familiar microelectronic field-effect transistor when it is switched on. The composition, shape, and size of the island gives the different types of solid-state nanoelectronic devices their distinct properties. Controlling these factors permits the designer of the device to employ quantum effects in different ways to control the passage of electrons on to and off of the island.

**B. Resonant-tunneling devices**

Here, we focus primarily on explaining the operation of resonant tunneling devices, because they employ quantum effects in their simplest form [1]. Presently, these devices usually are fabricated from layers of two different III/V semiconductor alloys, such as the pair GaAs and AlAs. The simplest type of resonant tunneling device is the resonant tunneling diode (RTD).

As depicted in Figure 2(a), a resonant-tunneling diode is made by placing two insulating barriers in a semiconductor, creating between them an island or potential well where electrons can reside. Resonant-tunneling diodes are made with center islands approximately 10 nanometers in width. Whenever electrons are confined between two such closely spaced barriers, quantum mechanics restricts their energies to one of a finite number of discrete "quantized" levels. This energy quantization is the basis for the operation of the resonant-tunneling diode.

The only way for electrons to pass through the device is to "tunnel," quantum mechanically, through the two barriers. The probability that the electrons can tunnel is dependent on the energy of the incoming electrons compared to the energy levels on the island of the device. As illustrated in Figure 2(b), if the energy of the incoming electrons differs from the energy levels allowed inside the potential well on the island, then current does not flow. The device is switched "off."

However, when the energy of the incoming electrons aligns with that of one of the internal energy levels, as shown in Figure 2(c), the energy of the electrons outside the well is said to be "in resonance" with the allowed energy inside the well. Then, current flows through the device--i.e., the device is switched "on."

By adding a small gate electrode over the island of an RTD one may construct a somewhat more complex resonant tunneling device called a resonant tunneling transistor (RTT). In this three-terminal configuration, a small gate voltage can control a large current across the device. Because a very small voltage to the gate can result in a relatively large current and voltage across the device, amplification or "gain" is achieved. Thus, an RTT can perform as both switch and amplifier, just like the conventional bulk-effect transistor.

Unlike conventional bulk effect transistors which usually have only two switching states, "on" and "off," resonant-tunneling devices like RTDs and RTTs can have several switching states. This occurs because the quantum well on the island may exhibit several possible energy levels.

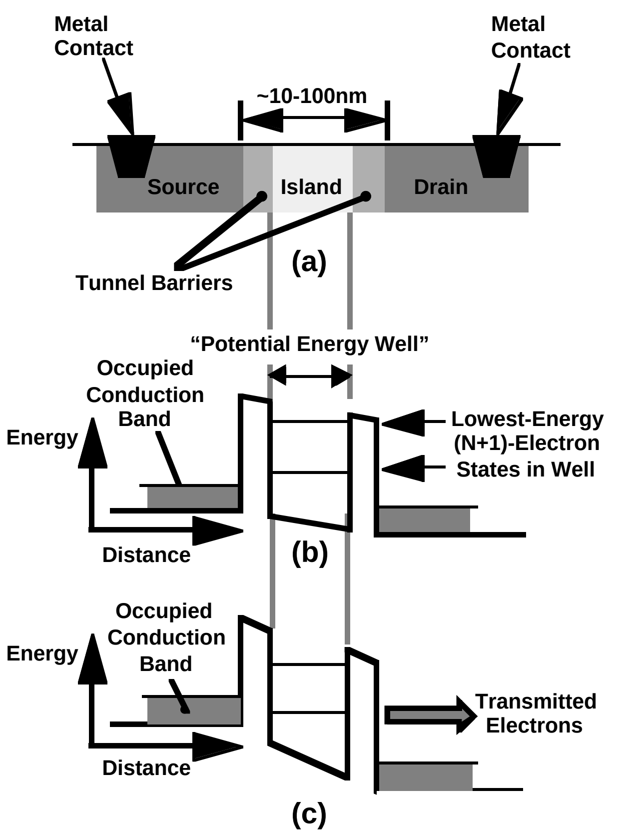


**Figure 2. Operation of Solid-State Resonant Tunneling Diode**

Thus, as the voltage bias on an RTD is increased from zero, where it is "off," the device initially switches "on" when the first energy level comes in resonance with the incident electrons. Then, it switches off again as the bias is increased further, past resonance. However, if there is a second energy level in the quantum well, then the device can switch on again as the bias voltage of the RTD (or the gate voltage of an RTT) is increased still further. This multistate switching behavior permits each device to "count higher" and represent more logic states.

### C. "Hybrid" Microelectronic-Nanoelectronic Resonant Tunneling Transistors

Purely nanometer-scale RTTs tend to be difficult to fabricate with sufficient uniformity in large quantities because of their relatively complex structure, small size, and the sensitivity of the effects they employ. However, there are also nanoelectronic devices which are "hybrids" of solid-state quantum-effect devices combined with micron-scale transistors. One such hybrid transistor-like device, the RTD-FET, is constructed by building tiny, nanometer-scale quantum-effect RTDs into the drain (or source) of a bulk-effect micron-scale FET. A schematic of such a device is shown in Figure 3.

Such a hybrid RTT can exhibit multistate switching behavior of the type described in the preceding section for

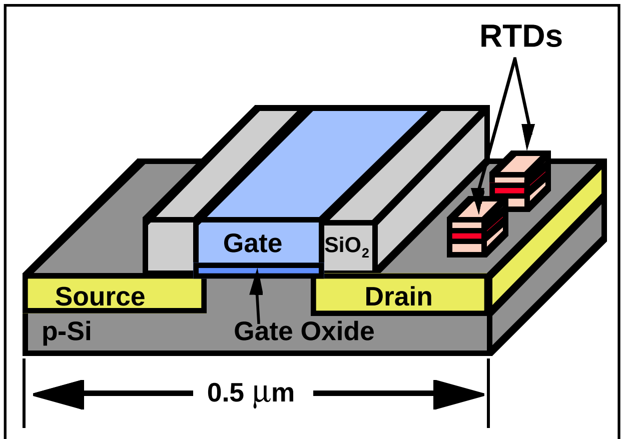


**Figure 3. "Hybrid" Microelectronic-Nanoelectronic Resonant Tunneling Transistor**

purely nanometer-scale RTTs. For this reason, the hybrid device can represent more logic states than a pure bulk-effect, microelectronic FET with the same "footprint" on the integrated circuit. Thus, the density of the *logic* can be increased using the multistate switching characteristics of hybrid micro-nanoelectronic RTTs, without appreciably increasing the density of the *devices* on an integrated circuit. Also, these hybrid RTTs share the advantages of low power and high speed exhibited by the purely nanoelectronic RTTs.

Most important, fabricating circuits with this relatively large, hybrid type of three-terminal RTT is easier than fabricating circuits with the much tinier, complex structures for purely nanoelectronic RTTs. For this reason a number of groups are experimenting with such devices. In recent months, robust prototype circuits based upon such hybrid devices have been demonstrated [4,5]. Hybrid logic can be viewed as an important, practical engineering step on an evolutionary path toward nanoelectronics. It should accelerate the availability of quantum-effect devices in integrated circuits with very dense functionality.

## III. MOLECULAR ELECTRONIC DEVICES

Ultimately, however, it will be desirable to build ultra-dense, low-power nanoelectronic circuits made from purely nanometer-scale switching devices and wires. Molecular electronics--using individual covalently bonded molecules to act as wires and switching devices--is the longer-term alternative for achieving this increase in density and for continuing Moore's Law down to the nanometer scale. Individual molecular switching devices could be as small as 1.5 nanometers across, with densities of approximately $10^{12}$ devices per sq. cm. This decrease in size could result in Terabyte memories on a chip and in excess of one trillion switching-devices on a single CPU chip. A primary advantage of molecular electronics is that molecules are natural nanometer-scale structures that can be made absolutely identical in vast quantities (approximately $10^{23}$ at one time). Also, synthetic organic chemistry--the

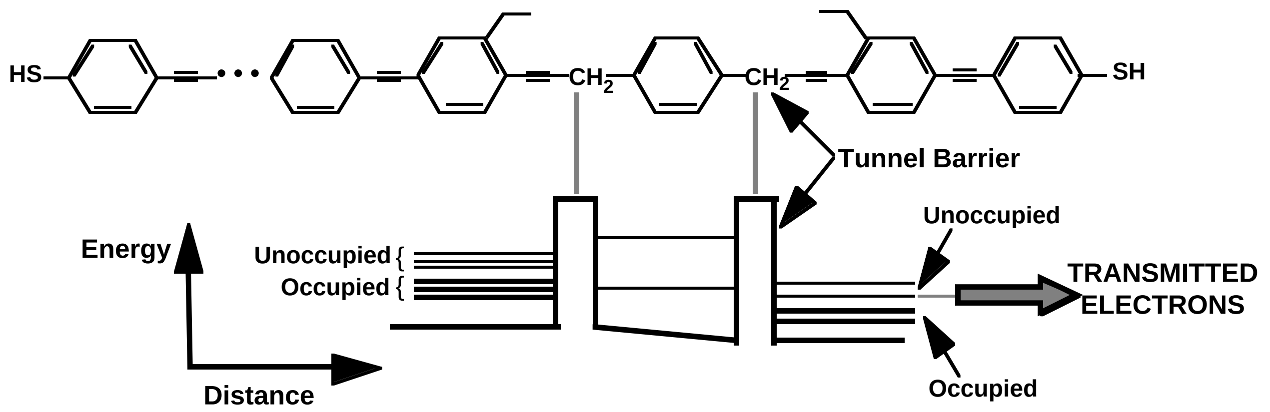


**Figure 4. Molecular Electronic Resonant Tunneling Diode**

chemistry of carbon-based compounds--offers more options for designing and fabricating these intrinsically nanometer-scale devices than the technology presently available for producing solid-state chips with nanometer-scale features. It has been shown during the past few years that small organic molecules can conduct and control electricity [6-11], that large organic biomolecules are conductive [12], and that individual molecules of the newly discovered molecular forms of pure carbon called buckminsterfullerenes ("buckyballs" and "buckytubes") have interesting and useful electrical properties [13-16].

Great progress is being made in understanding and harnessing the electrical properties of individual organic molecules. There has been particular experimental progress in demonstrating that individual molecules can conduct electrical current to function as wires and that they also can act as switches to turn this current on and off [6-11,13-16]. No logic circuits using these molecular switching devices have been fabricated yet. However, designs for such circuits have been proposed recently [17,18].

To some extent, the research and development of molecular electronic switches is recapitulating that for the corresponding solid-state devices, except on a much smaller scale. Thus, it is not surprising, that molecular electronic switching proposals and prototypes may be categorized into molecular analogs of solid-state diodes and analogs for solid-state three-terminal FETs.

A molecular analog of the solid state RTD that is discussed above in Section II.B is shown in Figure 4. This molecular RTD first was fabricated by Tour [9] and then demonstrated by a group led by Reed [10].

In the molecular structure depicted at the top of Figure 4, the hexagonally shaped components are known as benzene "rings." Chains of these rings, such as appear at the right and left ends of the molecule in the figure have been shown to function as conductive "molecular wires" [6,7]. The "$CH_2$" groups (termed "methylene" groups), on the other hand, act as insulators or "barriers" to electron flow. They can trap electrons on the single benzene ring between them, which forms an island. This molecular sandwich-like structure, with the island in the middle, produces a potential energy well like that sketched at the bottom of Figure 4.

Except that it is 10 to 100 times smaller, the molecular potential well in Figure 4 plainly resembles the well illustrated in Figure 2(b) for the solid state RTD. This similarity is the reason why the molecule sketched in Figure 4 behaves like an RTD.

## IV. CONCLUSION: CHALLENGES

Despite enormous recent progress in the fabrication and demonstration of nanoelectronic devices, many challenges remain. For solid state nanoelectronics, one of the most important challenges is to be able to produce reliably and uniformly in silicon the characteristic nanometer-scale features required for nanoelectronics: nanometer-scale islands, barriers, and "heterojunctions" between islands and barriers. Up to now, solid state nanoelectronic devices largely have been fabricated in III/V semiconductor compounds such as gallium arsenide and aluminum arsenide. It is believed, however, that silicon nanoelectronics would go a long way toward permitting the inexpensive mass manufacture of nanoelectronic devices.

For molecular electronics, one of the great challenges is to develop two-terminal and three-terminal devices than can be incorporated in circuits. Then, it must be demonstrated that such molecular switches can be used to make reliable logic, such as has been proposed recently [17,18].

Using either the solid-state or the molecular electronic approach, in order to fulfill the promise of nanoelectronics it will be necessary to refine greatly both the fabrication techniques and the architectural concepts to permit the useful assembly of small, low-power computing structures that contain trillions of nanoelectronic switching devices.

## ACKNOWLEDGEMENTS

The author wishes to thank the members of the MITRE Nanosystems Group for their collaboration in the nanoelectronics research investigations upon which this paper is based. He also wishes to thank many of his other colleagues at MITRE for their longstanding support of this research, notably David Lehman, Steven Huffman, Edward Palo, William Hutzler, and Karen Pullen. Thanks also are due to numerous colleagues outside MITRE for their encouragement, copies of their publications, and explanations of their research. This work was funded by a grant from The MITRE Corporation.

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