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Computing based on the physics of nano devices—A beyond-CMOS approach to human-like intelligent systems

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ABSTRACT

This paper proposes a new computing architecture to build human-like intelligent systems by best utilizing the physics of nano devices, or more specifically, the exotic current–voltage characteristics of nano-functional devices. The resonance characteristics arising from quantum effects in nano-scale devices are utilized as computing primitives of correlation and employed in building brain-mimicking VLSI systems. A number of subconscious processing taking place in our brains including early visual processing will be implemented in fine-grain parallel processing architectures using nano devices. In order to demonstrate the concept, the resonance characteristics of nano devices have been emulated by simple MOS bump circuitries, and real working proof-of-concept chips have been developed. Image recognition algorithms specifically developed for such brain mimicking systems are described, and the experimental results obtained form the measurement of analog, digital and mixed-signal VLSI chips as well as from computer simulations are presented as illustrative examples. In the last part of this paper, a perspective to the future is presented as a summary.

1. Introduction

The strategy for enhancing the computational power of CPU chips is quite straightforward. "Make transistors smaller, then more transistors can be integrated on a single chip". Following this well-known Moore's Law [1], the device dimensions have continuously been shrunk over past four decades, now approaching the nanometer rage. As a result, it is becoming increasingly difficult to keep traditional current–voltage characteristics in scaled CMOS devices, and a number of brick walls are awaiting us in the avenue of "More Moore". The problems are not only material and processing issues in fabricating devices but also the enhanced variability of device characteristics [2–5]. Further difficulty is being encountered in the architecture of CPU chips for building computers.

In the foreseeable future, the number of MOS transistors on a silicon chip will reach 10^{10}, which is equivalent to the total number of neurons in the neocortex of the human brain. However, it is not possible to make digital computers as intelligent as humans in such processing like *naïve perception, intuitive understanding* and *flexible decision making*. This is because the brain computing architecture is very different from those of digital computers. Therefore, by scaling approach only, it is very unlikely that we can build human-like intelligent electronic systems. It is mandatory, we believe, to explore *a new paradigm in computing in particular at the hardware level*. Furthermore, in the era of nano devices, circuit designers must change their mentality to accept the fact that miniscule devices are no longer reliable and reproducible in their characteristics. They must be prepared to design systems tolerant to probabilistic fluctuations in the elemental device characteristics. The special issue [6] presents a timely review on these subjects. Defect and fault tolerant schemes in logic circuits are discussed in [7–9], and in [10] a simplified cortical model implemented on the CMOL structure [11] is presented. In [12], a methodology to build logic gates on a nanodot array in which the inherent dot size fluctuation is rather beneficially used.

In miniscule devices of nanometer dimensions, very strange non-linear current–voltage characteristics are often observed due to quantum phenomena occurring in the device. If we could use such characteristics directly in computation, there would be a great opportunity in exploring highly functional circuits and systems by benefiting from the multiplicative effect of both enhanced functionality/device and their vast-scale integration. However, how to use such exotic *I*–*V* characteristics to build computing systems is still an open question.

The purpose of this paper is to present an idea of how to use nano-functional devices in building systems. We propose to *utilize*

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the exotic characteristics of nano-functional devices to build human-like intelligent systems. The basic functionality of "intelligence" is produced by the resonance characteristics of quantum devices. The functionality of such systems is enhanced in proportion to the total number of devices on the chip. Therefore the approach is best fitting to the vast-scale integration enabled by nano-scale devices. In addition, since the human-like decision is realized based on the *majority voting principle*, the system operation is not very sensitive to the fluctuation in elemental device characteristics. Therefore, we can provide an answer to the question how we can utilize the exotic non-linear characteristics of nano devices to build computing systems that exhibit performances far superior to those of "More-Moore" digital computers.

2. Resonance characteristics in three-terminal devices

Quantum effects produce non-linear *I–V* characteristics markedly different from those in traditional devices as exemplified in Fig. 1. The tunnel diode is a two-terminal device and its differential negative resistance (DNR) is utilized in high-frequency oscillators. However, in order to explore circuit applications the development of three-terminal quantum-effect devices is essential. A new functional resonant-tunneling bipolar transistor was developed in 1985 [13,14], which is a typical three-terminal device having a negative transconductance. Such three-terminal quantum-effect devices provide a lot of opportunity of building high-functionality circuits. Here, by "high-functionality" it is meant certain functions can be implemented in much simpler circuit configurations as compared to traditional device counterparts. Following the work of [13], a resonant-tunneling MOSFET (Fig. 2) was proposed [15,16] and analyzed by simulation in [17,18]. In the present paper, we propose to use such characteristics to build human-like intelligent systems.

What we are proposing here is to utilize the resonance characteristics of Fig. 3a to represent a fragmental knowledge. Any devices having such bell-shaped characteristics (or U-shaped characteristics as well) can be utilized. The device yields the maximum (or minimum in the case of U-shaped characteristics) response to the input when V_G coincides with V_M. If V_G is deviated from V_M, the response reduces. Namely, such a device can represent how close an input V_G is to the memorized knowledge V_M. Therefore the value of V_M represents a fragment of a specific knowledge pattern. In this regard, the position of V_M must be made programmable. However, in general it is difficult to program the resonance voltage to an arbitrary value, because the peak position is determined by quantized energy levels. The problem can be resolved by just inserting a capacitor and control the amount of charges on the floating node as shown in Fig. 3b. The charge control can be conducted by tunneling and/or hot electron injection or by just attaching a switching transistor to the floating node. If a resonance circuit is composed of plural such devices, the circuit yields the similarity between the input vector **X** and the memorized pattern **M** (Fig. 4a). This can serve as a basic building block of an associative processor. By integrating a huge number of such resonance circuits on a single chip, an expert knowledge system can be realized as shown in Fig. 4b. Element values of an input vector are broadcasted to all resonance circuits by interconnects and the one showing the maximum response is selected by a winner-take-all circuitry (the maximum location identifier). Thus the most similar event to the input is automatically recalled from the memory of past experience. Such a hardware brain computing scheme has been derived from *psychological inspiration*, i.e. by observing the mental activities within ourselves [19]. We have already developed associative processors working in this principle [20–25] and have demonstrated such a system can be applied to robust image recognition [23,24]. Typical examples are demonstrated later in Sections 4 and 5.

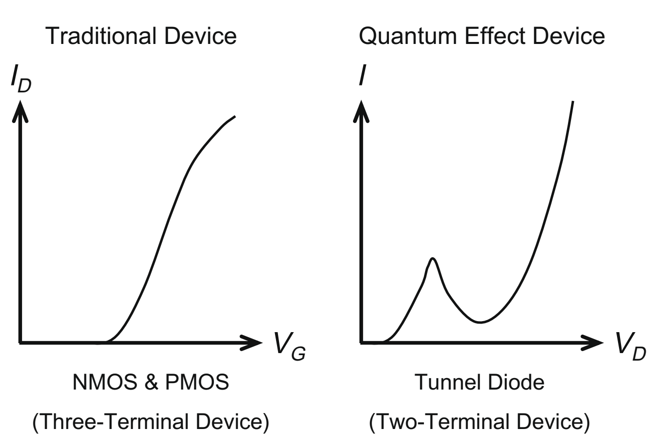

Fig. 1. Nonlinear current voltage characteristics of MOSFET and tunnel diode.

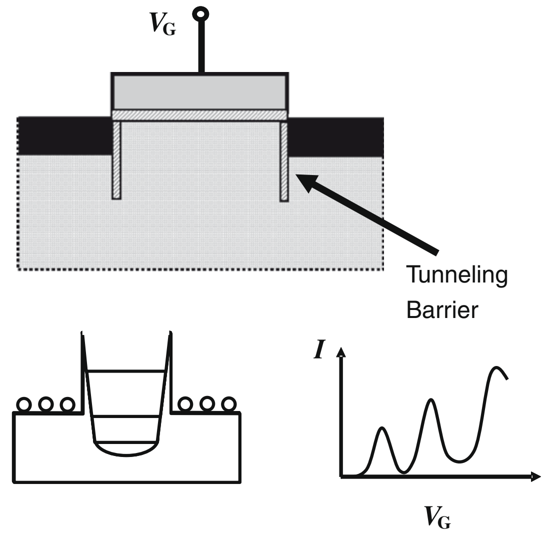

Fig. 2. Resonant tunneling MOSFET proposed in [15,16] and studied in [17,18].

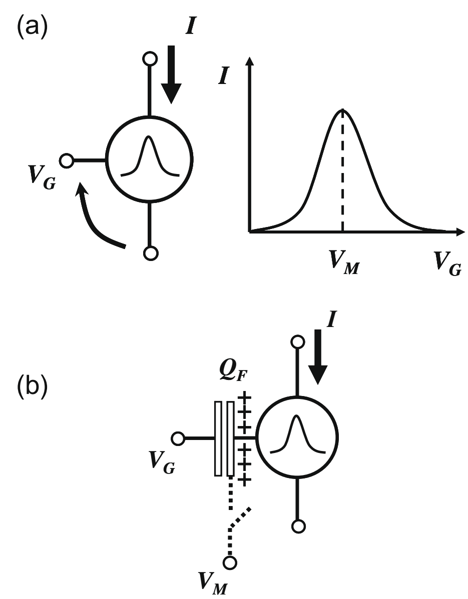

Fig. 3. Quantum-effect device having resonance-type *I–V* characteristics.