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Invited

Four-Terminal Device Electronics for Intelligent Silicon Integrated Systems

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We will propose the concept of high-functionality "four-terminal device" which surpasses the three-terminal devices like MOSFET's and bipolar transistors in the ability of current control functions. The enhanced functionality at the very elemental transistor level is most essential to create human-like intelligence at system levels. Neuron MOSFET (νMOS), a multiple-input- terminal floating-gate device, is taken as an example of four-terminal device, and the implementation of intelligent electronic circuits has been demonstrated. The binary-multivalue-analog merged algorithm conducted by νMOS circuits is a key to realize highly flexible computation while assuring the noise immune feature of the binary logic.

1. Introduction

Thanks to the great advancement in the microfabrication technologies, giga transistor integration on a chip has become possible. With such a huge number of transistors on a single silicon chip, however, the electronic systems are still far from being intelligent as compared to biological systems in many respects.

A frog finds a fly passing through and catches it in a moment. This action has been created by a series of information processing carried out within this small creature. This includes catch of the fly image on a retina, identification of the object as his meal, computation of its expected motion followed by the activation of motor neurons to catch the fly. Such a real-time action, however, is impossible even with the most advanced super computers of today. Something important is lacking in the present-day electronic computing systems.

What we are presenting in this paper is that the enhancement in the functionality of an elemental transistor is most essential in order to circumvent the difficulty. Namely, the introduction of the concept of "four-terminal device" that functionally surpasses the so-called three-terminal devices like MOS transistors and bipolar transistors is critically demanded.

2. Human Brain vs. Computers

Basic hardware computing performances are compared between a human brain and a super computer in Fig. 1. The switching speed of a transistor, the very basic element of a computer, is $\sim 10^{-11}$sec, while the response time of a nerve cell neuron is approximately 0.1sec. The transistor is 10^{10} times faster than its biological counterpart. Signals on metal interconnects propagate at a speed of light while nerve impulses propagate only at a speed of 2 ~ 3m/sec in the brain. Again 10^7 times faster for electronic systems. Why is it impossible at all for an electronic system to carry out a real-time action?

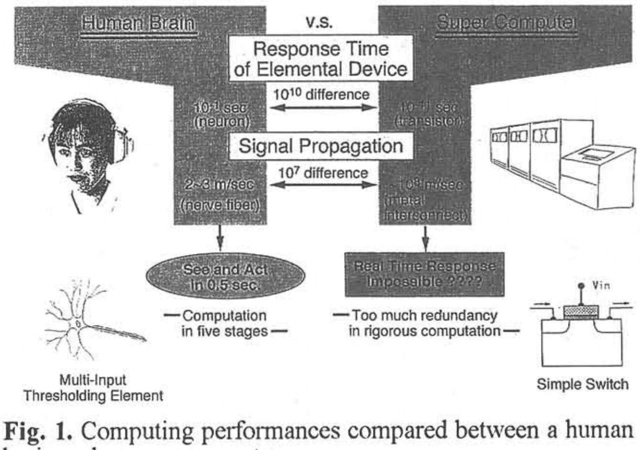


Fig. 1. Computing performances compared between a human brain and a super computer.

The most important difference exists in the basic functionality of an elemental device: a transistor is a simple switch controlled by a single input while a neuron is a multiple-input thresholding element. This difference does not seem very significant but creates a tremendous difference at the system level in terms of algorithm and architecture. The very rigorous on-and-off switching characteristics of a "three-terminal" transistor is the very reason for the rigidness we feel with digital systems. Seemingly flexible features of PC's are no more than a illusion produced by elaborate software technologies. Behind the software, a tremendous amount of numerical calculations are being conducted on the hardware, making a real time response of the system impossible.

"Flexibility," "fine-grain hardware parallelism," and "real-time programmability" are three key features required for integrated circuit hardware in order to realized intelligent functions at a system level.

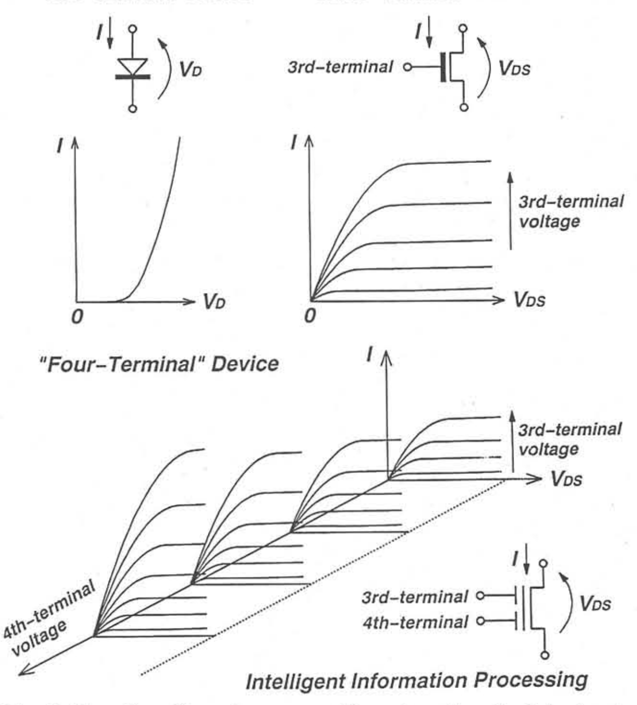


Fig. 2. Functionality enhancement from two-terminal device to four-terminal device.

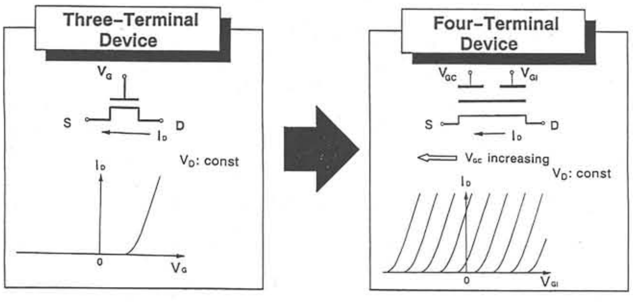


Fig. 3. Comparison between three-terminal device and four-terminal device (νMOS).

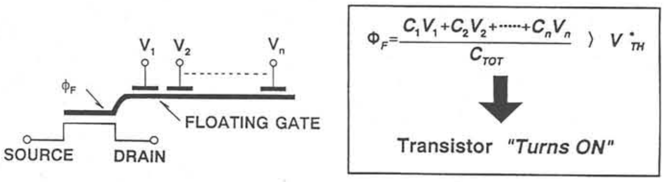


Fig. 4. Schematic of a neuron MOS transistor.

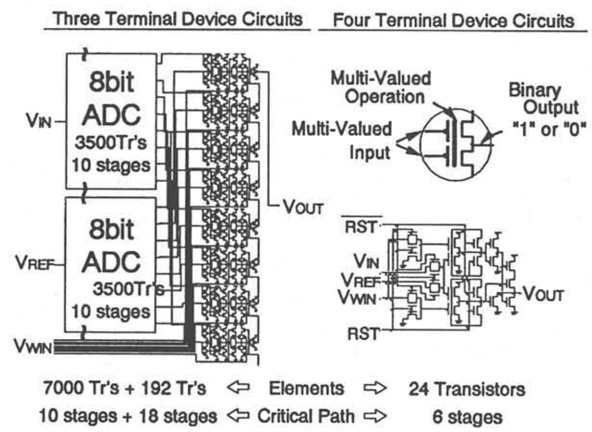


Fig. 5. Real-time rule-variable data matching circuits.

3. Four-Terminal Device Electronics

Fig. 2 summarizes the functionality enhancement in a device from two terminal device to four terminal device[1]. In a two-terminal device, like a *pn* diode or a vacuum diode, the current flowing through the device is uniquely determined by the voltage difference between the two terminals. Diodes can be only used as rectifiers. No sophisticated applications can be generated from such a primitive functionality. In a three-terminal device, however, like an MOS transistor, a bipolar transistor or a vacuum triode as well, the current flowing through the two main terminals is controlled by the voltage signal given to the third terminal. As a result, the current controllability has been expanded to a two dimensional span. Such a functional enhancement in the current control yields a great flexibility in constructing more complex systems. This has enabled us to develop the concept of electronic circuits, including amplifiers, oscillators, and digital computing systems. It is not too much to say that the electronics in the 20th century has been created by three-terminal devices.

In the three-terminal device, however, the current (drain current) is uniquely determined by the third-terminal voltage (gate voltage) when the drain voltage is fixed (see Fig. 3), thus creating the function of a current switch. The feature is quite compatible to implementing very rigid binary digital algorithms based on the Boolean algebra, but far from being flexible. In a four-terminal device, however, the current is not uniquely determined under the same circumstance because the additional fourth terminal can give an opportunity to further control the output current. Namely, the manner in which the current is control by the third terminal is further modified by the voltage signal given to the fourth terminal. In other words, the four-terminal device is a device in which the degree of freedom in current controllability is increased to a three dimensional span as shown in Fig. 2. Such a functionality enhancement in the device is most essential in realizing flexible information processing scheme on the hardware.

A neuron MOSFET (νMOS)[2] shown in Fig. 4 is the first four-terminal device, which eventually has multiple fourth terminals. Due to its functional similarity to the mathematical model of a neuron[3], we named the device neuron MOSFET (neuMOS or νMOS for short).

4. Binary-Multivalued-Analog Merged Computation

Fig.5 shows the real-time rule-variable data matching circuits implemented by three-terminal devices (conventional CMOS) and four-terminal device (νMOS)[4,5]. The circuit gives an output of "1" when the two input signals (analog or Multivalued) are matched within the margin specified by a window signal. Such signal processing is very essential in handling image data. The big difference in the quantity of hardware is evident in the figure. In the pure digital case, the A/D converter overhead is too large to equip with each pixel in a two dimensional array. Therefore the sequential computation scheme is an inevitable choice, requiring a large computational powers of MPU's. The very small-scale implementation by the four-terminal device allows us to equip each pixel with the circuit. Hardware parallelithm thus achieved is undoubtedly faster than the sequential scheme and the only way to realize a real-time response of a system.

Such a great simplification in the hardware comes from the use of analog data in the circuit. But it should be stressed here that analog signals are only generated in the floating gate of νMOS' temporarily, and immediately the decision is made by the thresholding action of νMOS to yield the binary answer of "yes" or "no." This computation scheme is quite different from the pure analog computation in that the noise or errors generated in a stage do not propagate and accumulate. This hardware algorithm possesses the high-degree of flexibility of analog processing while preserving the rigorousness of the binary digital algorithm.

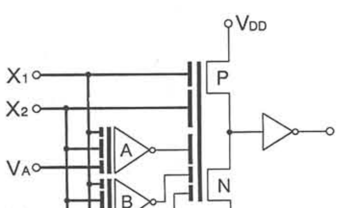
Based on this scheme, a new concept νMOS logic called *flexware* has been developed as shown in Fig. 6. The two-input *flexware* shown in Fig. 6(a) can represent all 16 possible Boolean functions with the identical hardware configuration. Each function is real-time selected by changing the control signals given to $V_A \sim V_B$ terminals. Figure 6(b) shows a photomicrograph of an eight-variable symmetric flexware circuit[4]. The circuit can represent all 512 symmetric Boolean functions for eight input variables in which each function is selected by a binary control code given to $V_A \sim V_I$ terminals. The circuit is composed of only 22 transistors (20 νMOS' and two regular MOS'). Such a great flexibility in altering the circuit function will allow us to develop a new-concept computer architecture in which the hardware organization is real-time alterable by operation codes or even by the results of current computation.

Fig. 7 shows a photomicrograph and the circuit architecture of νMOS associative memory which can search for the most resembling data in the stored memory corresponding to the input data in a fully parallel architecture. The binary data are matched at each cell level and summed over a word on the νMOS floating gate, yielding the Hamming distance. Then the minimum distance search is conducted by a νMOS winner-take-all circuit [6]. When the binary SRAM cell of the memory is replaced by a multi-valued associative DRAM cell[7], multi-valued vector search for the most similar can be conducted also in a fully parallel architecture. These features are extremely important in conducting intelligent data processing on the hardware.

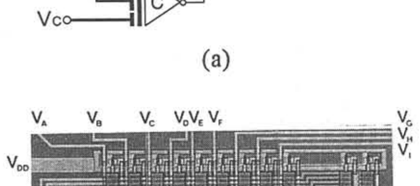
Fig. 8 represents a photomicrograph of νMOS neural network equipped with an on-chip self-learning circuitry[8]. Since νMOS itself has the function of a neuron, the learning ability of the network is determined by the characteristics of the synapse cell. We developed a new EEPROM synapse memory cell featuring an excellent linearity in the weight updating characteristics[9], and on-chip learning control circuitries were fully integrated on a chip[10]. In this manner the real-time programmability of the hardware has been also established.

5. Conclusions

In order to realize human-like intelligent electronic systems, it is most essential to enhance the functionality of an elemental transistor, the very basic building element of all electronic systems. For this purpose, we have proposed the concept of four-terminal device and demonstrated its significance by taking the neuron MOSFET as the first example of a four-terminal device. The binary-multivalued-analog computation conducted by νMOS circuitries and high-precision processing technologies that enable such new architecture circuits are the key to realize human-intelligence electronic systems in the 21st century.

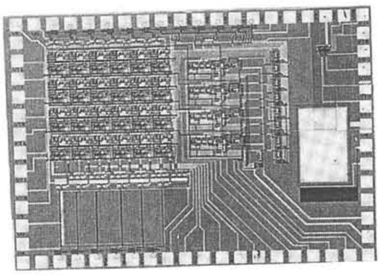


(a)

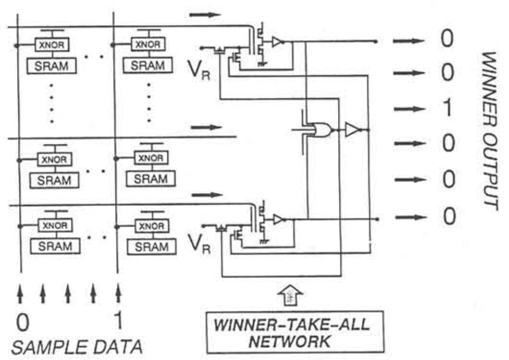


(b)

Fig. 6. (a)Circuit diagram of 2-input flexware; (b) Photomicrograph of eight-input flexware.



(a)



(b)

Fig. 7. νMOS associative memory: (a) Photomicrograph of a test chip; (b) Circuit diagram.

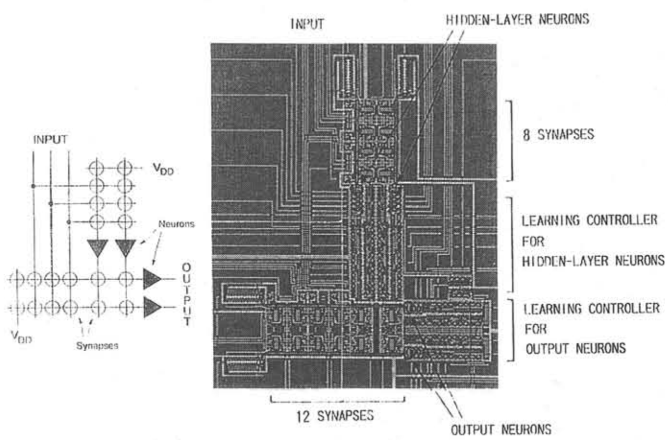


Fig. 8. Experimental νMOS neural network having on-chip learning circuitry, including three input units, two hidden-layer neurons, two output neurons and 20 synapses.

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