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A Current-Mode νMOS Circuit for Cellular-Automaton Devices

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We developed a functional circuit, the current-mode νMOS circuit, for implementing cellular-automaton image processing on an LSI chip. The current-mode νMOS circuit can provide various cell functions that are useful for morphological picture processing. The circuit is similar in its operation to the known νMOS (neuron MOS) threshold circuit but can operate in far lower power dissipation. The current-mode νMOS circuit will open prospects for developing novel image-processing LSIs.

1. Introduction

The cellular automaton is a parallel processing system suitable for high-speed picture processing. To construct cellular automaton devices on LSIs, we must develop a cell circuit that can produce required cell functions in compact construction with low power dissipation. This paper proposes one such cell circuit: *a current-mode νMOS threshold circuit.*

The cellular automaton is a data-processing system that consists of many identical processing elements (cells) regularly arrayed on a plane. Each cell changes its state in discrete time steps through the interaction with its neighboring cells. The data that the cellular automaton manipulates is a pattern of the cell states (i.e., a matrix whose elements represent states of the arrayed cells). The cellular automaton receives an input pattern and transform the pattern into various differing patterns with time steps; at an opportune moment, the transformed pattern is retrieved as an output. The cellular automaton has potential applications to morphological processing on binary pictures. It can be expected to provide high-speed picture processing LSIs because its operation is inherently parallel.

The crucial problem in developing such cellular automaton LSIs is that the LSI has to be implemented in one chip with *fully parallel construction* (one processing circuit for each cell). Because picture-processing applications require a large number of cells, it is therefore required that the unit cell devices should be small both in area and in power dissipation. It is difficult, however, to construct such cell devices with ordinary digital logic circuits. So we must develop a novel cell device for constructing cellular automaton LSIs.

To construct such a cell device, we have developed a threshold circuit based on current addition and subtraction. We call this circuit a *current-mode ν-MOS circuit* because the operation of the circuit is similar to that of the known ν-MOS (neuron MOS) threshold circuit. The current-mode ν-MOS circuit can provide a promising cell devices for morphological picture processing.

In the following sections, first, we outline the cellular automaton operation and describe various cell functions required for morphological picture processing (Section 2). We then develop the current-mode v-MOS threshold circuit and, by using this circuit, design cell devices for implementing various cell functions (Section 3). The operation of the cell devices is demonstrated by computer simulation to demonstrate that the designed cell devices can produce the desired cell functions correctly in low power dissipation (Section 4).

2. Cellular Automaton System for Picture Processing

2.1 Pattern transformation using the cellular automaton

A cellular automaton is a parallel processing system that consists of a large number of identical processing cells regularly arrayed on a plane (Fig. 1). Each cell has a binary (or multiple-valued) state, and all the cells change their states synchronously in discrete time steps according to a given local interaction rule (a *cell function*). Each cell determines its subsequent state on the basis of the current states of its own and of its neighboring cells. In this way, the cellular automaton transforms the pattern of the cell states into various differing patterns with time steps according to a given cell function. (For detailed explanations, see Refs. 1 and 2.)

We here assume a binary cell state (1 or 0) and consider the *eight* neighbors in determining the subsequent state of each cell. If each cell is regarded as a pixel and its 1-0 state as a black-white level of the pixel, then the operation of the cellular automaton is the same as the morphological processing on binary pictures; the cell functions correspond to the local operation for morphological processing.

2.2 Cell function of the cellular automaton

The operation of the cell is to produce its subsequent state in response to the nine inputs (the 1-0 states of its own and of 8-neighbor cells) according to a given cell function. The cell function depends on what morphological processing is required. It is mostly a complex function that cannot be represented by a simple Boolean expression. We here illustrate, in Figs. 2(a) through 2(d), several examples that are symmetric and relatively simple but often used in picture processing ("symmetric" means that each neighboring cell makes an equal contribution toward determining the subsequent state of the center cell). The examples are variable-threshold functions whose thresholds are controlled by the current state of the cell, and they cannot be constructed compactly by using ordinary logic gates. (Many cell functions frequently used are threshold, majority decision, or weighted-input functions.) To implement such cell functions on electronic circuits, we have developed a novel threshold circuit: the current-mode vMOS threshold circuit.

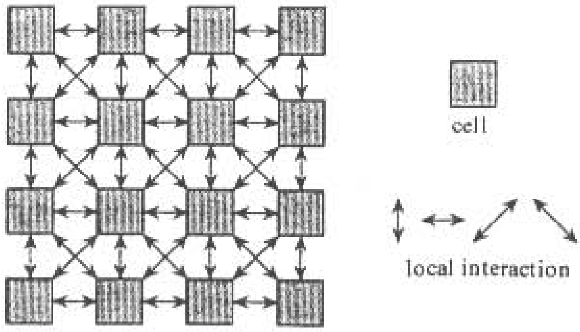
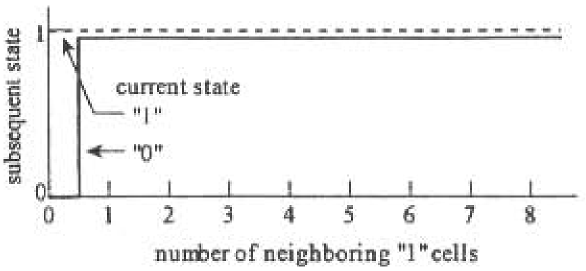


Fig. 1 Cellular automaton. An information processing system consisting of a large number of identical processing cells with local interactions.

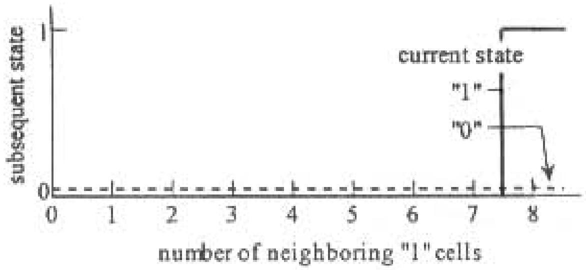
3. Cell Devices Using the Current-Mode vMOS Threshold Circuit

3.1 Current-mode vMOS threshold circuit

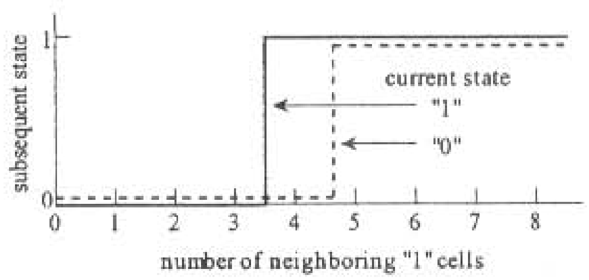
The circuit we have developed carries out threshold logic operation on the basis of current addition and subtraction. The concept of the circuit is illustrated in Fig. 3. The circuit consists of three constituents: threshold-current sources, an offset current source, and input-current sources with switches controlled by binary input signals (the switch is on for an input of 1). Each threshold-current source injects current *I0* into the output node, and each input-current source



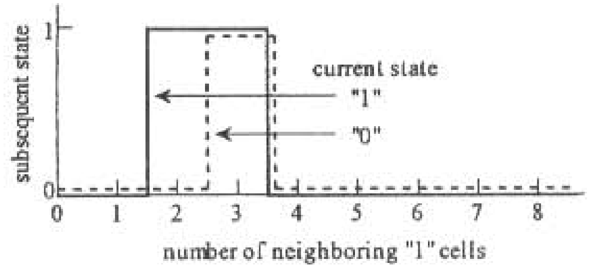
(a) *Dilation*. With this cell function, an object grows uniformly by a single-pixel-width ring of exterior pixels.



(b) *Erosion*. With this cell function, an object shrinks by a single-pixel-width ring of interior pixels.



(c) *Majority black*. It is useful for filling small holes and eliminating small projections in objects. It can also be used for noise elimination.



(d) *Game-of-Life*. The best-known cell function for the cellular automaton.

Fig. 2 Various cell functions used of picture processing. Simple and symmetric examples are shown.

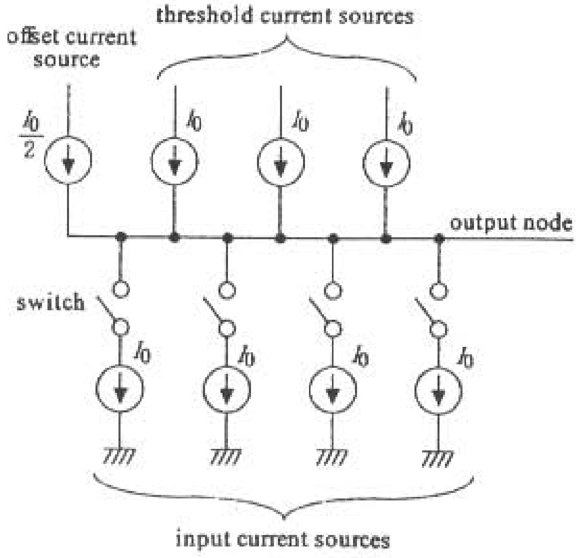


Fig. 3 Concept of the current-mode vMOS circuit. The switches are controlled by input signals.

drains current *I0* from the output node through the switch. The offset current source injects current *I0* / 2 into the output node.

The circuit accepts 1-0 input signals and compares the number of "1" inputs with the number of the threshold-current sources to produce the corresponding output voltage. If the number of "1" inputs is larger than that of the threshold-current sources, then a net current is drained from the output node and, consequently, the output node voltage falls to a "0" state; otherwise a net current is injected into the output node and, in consequence, the output node voltage rises to a "1" state.

The operation of this circuit is similar to that of the vMOS threshold circuit. The vMOS circuit (Fig. 4) takes a sum of its inputs on a floating gate that is capacitively coupled to the input terminals. And it generates an 1-0 output depending on whether or not the sum of inputs is greater than the inverter threshold (for details of the vMOS circuit, see Refs. 3 and 4). In our circuit, taking the sum of inputs and comparing the sum with the threshold are carried out through the current addition and subtraction on the output node. The advantage of our circuit is that low-power operation can be achieved simply by reducing the value of current in the current sources. (The vMOS circuit often produces large short-current power dissipation because, in threshold logic application, its floating gate is frequently set at intermediate voltages between 1 and 0.)

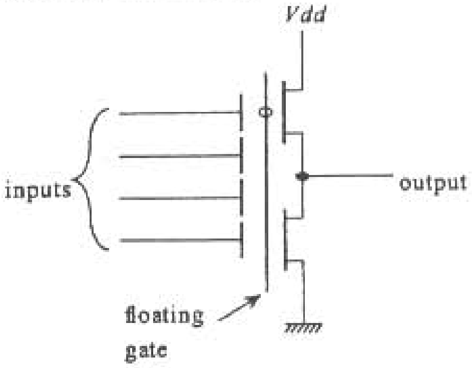


Fig. 4 The vMOS circuits (neuron MOS circuit).

3.2 Constructing cell devices

By using the current-mode vMOS circuit, we constructed unit cell circuits to implement several cell functions. Examples for the cell functions given in Fig. 2 are illustrated in Figs. 5 through 7. Every circuit accepts nine inputs (a binary voltage $V0$ that represents the current state of the cell, and eight binary voltages $V1$ through $V8$ that represent the current states of 8-neighbor cells) and produces a binary output voltage that represents the subsequent state of the cell.

(a) Dilation-erosion cell circuit (Fig. 5)

The cell functions dilation and erosion are frequently used for morphological processing in combination with each other. So we implemented both functions in a single circuit as shown in Fig. 5. The cell circuit consists of three subcircuits: a current-mode vMOS threshold circuit, a bias circuit, and an output buffer. The current-mode vMOS circuit contains input-current sources $M1$ through $M8$, threshold-current sources $M11$ through $M18$, and offset-current sources $M0$ and $M10$. The total circuit current is determined by external bias voltage Vb. The bias circuit generates bias voltages for the threshold-current sources and the offset-current source $M10$. The circuit accepts as inputs the current cell-state signal $V0$ and 8-neighbor cell signals $V1$ through $V8$, and produces the subsequent cell-state signal $Vout$. The functions dilation and erosion is switchable by control signal Vc that changes the polarity of a net offset current. The circuit operates in dilation if Vc = "1" (Vdd), and erosion starts if $Vc = 0$.

(b) Majority-black cell circuit (Fig. 6)

The function of majority black can be achieved by using the dilation-erosion circuit with some alteration. But we here present another circuit of more concise construction. In this circuit, the thresthold-current sources are controlled by the input signals as well as the input-current sources are.

(c) Game-of-Life cell circuit (Fig. 7)

The function of Game-of-Life is a double-threshold function whose lower threshold is controlled by the current state of the cell. It can be achieved by combining two current-mode vMOS circuits.

To achieve low power dissipation, each cell circuit is operated at a low current of 10 µA or less. In such a low current region, cell circuits cannot be operated at high speed. But this is not a problem in cellular automaton devices because all the cell circuits operate in parallel to produce a high performance in total processing. A cell speed of 1-MHz clock operation suffices for most picture-processing applications.

4. Operation of the Cell Devices

We confirmed by computer simulation that developed cell circuits operate correctly for all possible input combinations. The results are shown in Figs. 8 and 9, taking the majority-black cell circuit in Fig. 6 as an example. In simulation, a set of 1.5-µm CMOS device parameters was used (Vdd = 5 V). The unit current in current sources (i.e., the current in

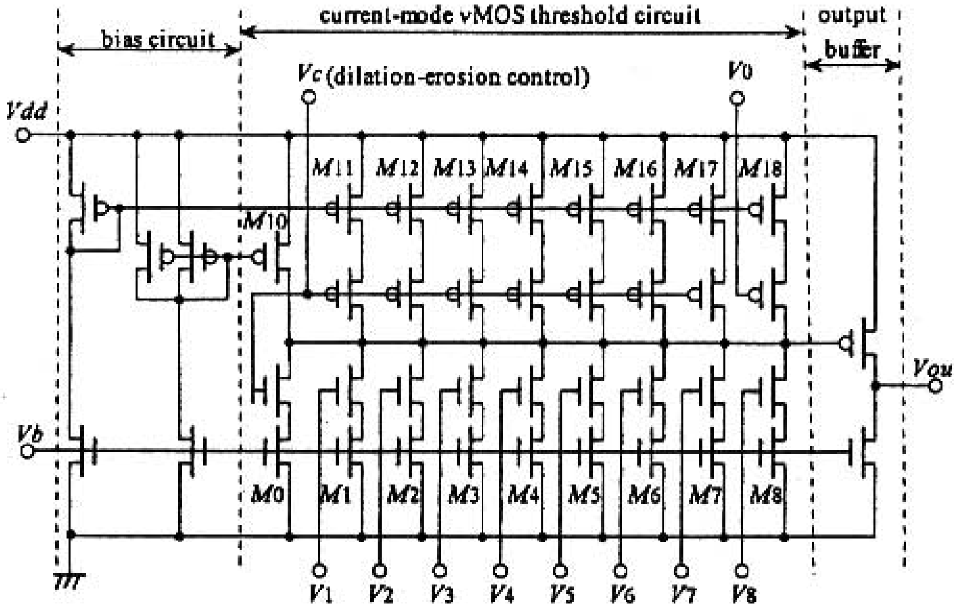


Fig. 5 Dilation-erosion cell circuit.

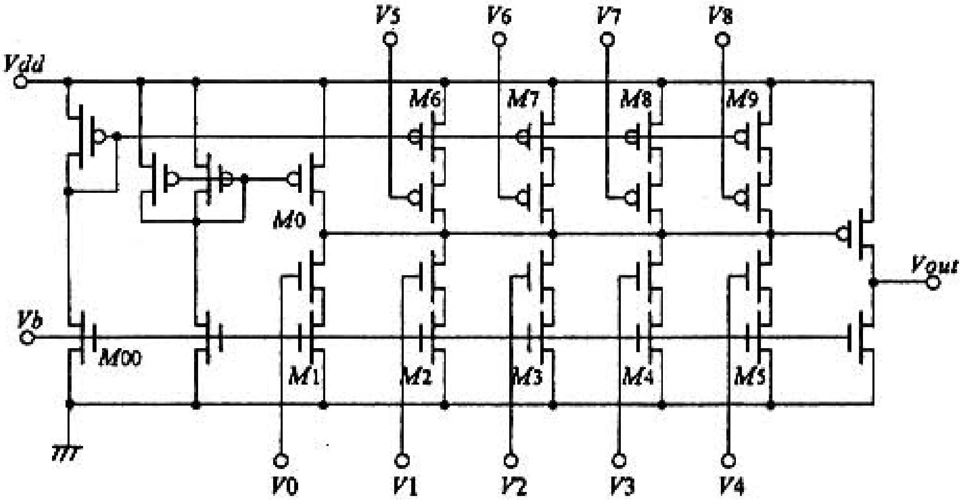


Fig. 6 Majority-black cell circuit.

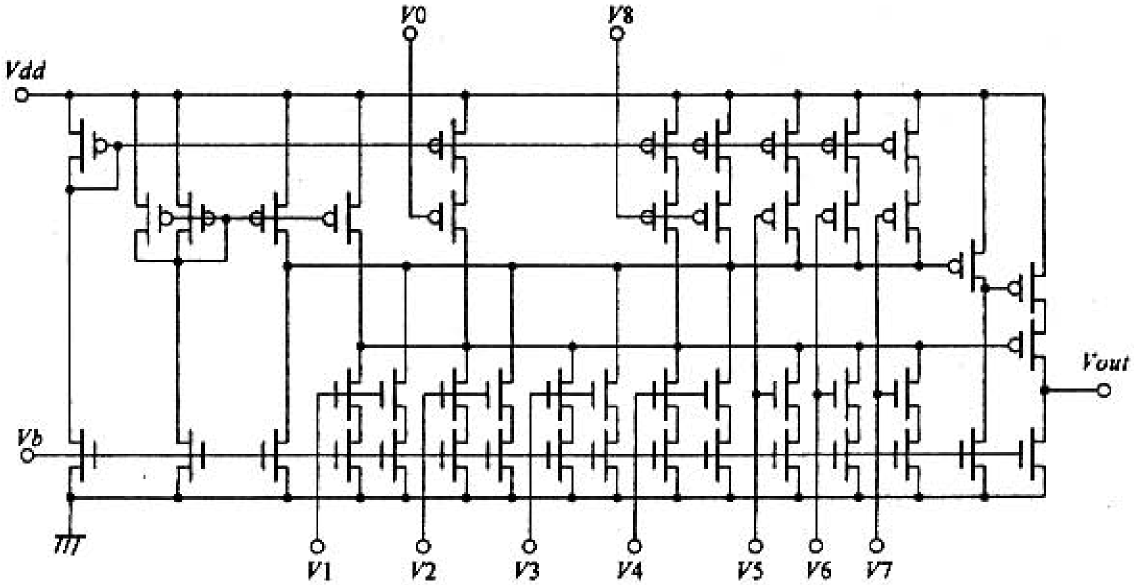


Fig. 7 Game-of-Life circuit.

*M*00 in Fig. 6) was set at 1.2 μA by adjusting external bias voltage *Vb*.

The transfer characteristic (cell function) of the circuit is illustrated in Fig. 8. In this figure, the horizontal axis represents the number of "1" inputs (in eight inputs *V*1 through *V*8), which represents the number of 8-neighbor cells that are in state "1". The vertical axis represents the output *Vout* that represents the subsequent state of the cell. The threshold can be controlled by *Vc* that represents the current state of the cell and, consequently, the circuit produces the desired cell function.

The power dissipation is also plotted in Fig. 8. In this circuit, the power dissipation depends on which inputs are in state "1" as well as on the total number of "1" inputs. Plotted in the figure is the maximum power dissipation for a given number of neighboring "1" inputs.

The speed capability of the circuit is illustrated in Fig. 9. In the simulation, the circuit was set up such that its four inputs *V*1 through *V*4 were fixed at 0 and four inputs *V*5 through *V*8 were fixed at 1 (= *Vdd*). Then 1-0 square wave voltage was applied to input *V0* at various frequencies. The figure illustrates the result for 2.5-MHz input frequency. The delay time was 60 ns in this example. This operation speed suffices for most image processing applications.

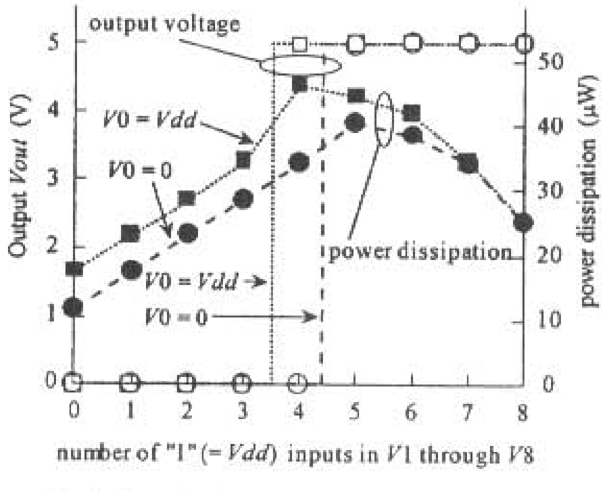


Fig. 8 Transfer characteristic and power dissipation in the majority-black cell circuit given in Fig. 6.

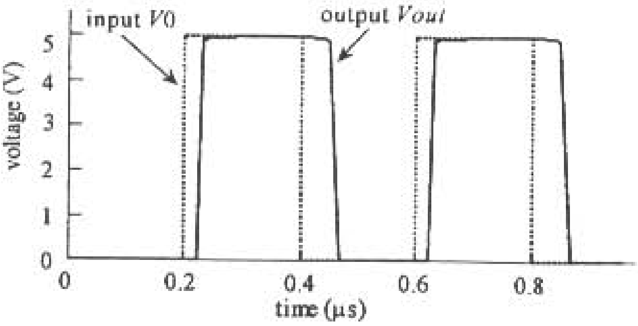


Fig. 9 Operation speed of the majority-black cell circuit given in Fig. 6. Inputs *V*1 through *V*4 are fixed at 0, and *V*5 through *V*8 are fixed at *Vdd*.

5. Conclusions

We developed a functional circuit, the current-mode vMOS circuit, for implementing cellular-automaton image processing devices onto an LSI chip. The current-mode vMOS circuit carries out variable-threshold logic operation and can provide various cell functions that are useful for morphological picture processing. The circuit is similar in its operation to the known vMOS circuit but can operate in far lower power dissipation. The current-mode vMOS circuit will open prospects for developing novel image-processing LSIs.

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