

A CMOS Watchdog Sensor for Certifying the Quality of Various Perishables with a Wider Activation Energy*

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SUMMARY We developed a CMOS watchdog sensor that simulates the changes in quality of perishables such as farm and marine products. The sensor can imitate a chemical reaction that causes the changes in the quality of perishables, with a wide range of activation energy from 0.1 eV to 0.7 eV. Attached to perishable goods, the sensor simulates the deterioration of the goods caused by surrounding temperatures. By reading the output of the sensor, consumers can determine whether the goods are fresh or not. This sensor consists of subthreshold CMOS circuits with a low-power consumption of 5 μ W or less.

key words: CMOS, sensor, subthreshold, translinear, low power, quality guarantee

1. Introduction

In this paper, we propose a CMOS integrated circuit sensor that is attached to perishable goods and simulates their deterioration during distribution from producers to consumers.

Controlling the quality of consumer goods in a distribution process is very important but not easy for perishables such as farm, marine, and dairy products. To guarantee their quality of these perishable goods, producers generally stamp an expiration date—for example, ‘Use by Feb. 28, 2006’—on the package of the goods before shipping. However, producers have no way of knowing the conditions of distribution in detail; the goods might be distributed under favorable conditions or they might be distributed under bad conditions of high temperatures. To prepare for the worst, producers have to set the expiration date rather short. In consequence, considerable amounts of perishable goods are thrown away only because the expiration date has passed, though the goods are still eatable.

This problem can be solved by developing a smart sensor, or a watchdog sensor, that monitors the deterioration of perishable goods during distribution from producers to consumers. Such monitoring can be performed by electrically simulating the chemical reaction that causes the deterioration of perishables. The sensor is attached to the perishable goods and is carried from producers to consumers along with the goods. It experiences the surrounding temperatures and simulates the deterioration of the goods caused by the

temperature. By reading the output of the sensor, consumers can determine whether goods are fresh or not. Previously, Hirose and others proposed a prototype chip of watch-dog sensor circuits composed of operational amplifiers [1], [2]. However, the circuit has a difficulty to emulate a large activation energy of the reaction. In general, the activation energy of spoiling reactions is around 0.5 eV [3]. From this fact, the circuit, which consisted of only analog circuit, cannot emulate a large activation energy.

In this paper, we propose an improved watchdog sensor whose simple circuitry differs from the prototype device; it can simulate the deterioration of perishables with a wide range of activation energy from 0.1 eV to 0.7 eV, a range impossible for the prototype, by using both analog and digital circuit technique. In the following, Sect. 2 outlines the principle of the simulation for the deterioration of perishables. Section 3 describes the processing architecture and the circuitry of the sensor we propose. Section 4 illustrates the operation of the sensor with simulation results for various values of activation energy.

2. Simulation of the Deterioration Process

2.1 Expressing the Changes in Quality of Perishables

The deterioration process of perishables can be approximately expressed by a simple chemical reaction, $A + B \rightarrow C$, where A and B are the constituent elements of the perishables, and C is an undesirable spoiling substance produced by the reaction [3]. According to this reaction, the concentration of undesirable product [C] can be given by

$$[C] = [A]_0[B]_0k_0 \int_0^{t=t_1} \exp\left(-\frac{\Delta E_a}{k_B T}\right) dt, \quad (1)$$

where $[A]_0$ and $[B]_0$ are the initial concentrations of constituents A and B. The concentration of [C] corresponds to the deterioration and is greatly affected by the thermal history that the goods experience during their distribution process.

2.2 Simulating the Deterioration Process with CMOS Circuits

To simulate the deterioration process, Eq. (1), with electrical circuits, we use the transfer characteristics of a MOS-FET operated in the subthreshold region. The following is an excerpt from [1]. The subthreshold current I_D through a

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MOSFET is an exponential function of the gate-source voltage and is given by

$$I_D = I_0 \exp\left(\frac{e(V_G - V_{TH})}{\eta k_B T}\right), \quad (2)$$

where I_0 is a process-dependent parameter, e is the elementary charge, η is the subthreshold slope factor, and V_G is the input gate-source voltage for the MOSFET [4]. To imitate activation energy for the deterioration process, we prepared two MOSFETs biased by different gate-source voltages (V_{G1} and V_{G2}) and take the ratio of subthreshold currents (I_{D1} and I_{D2}) through the two MOSFETs. The ratio is given by

$$\frac{I_{D2}}{I_{D1}} = \exp\left(-\frac{\Delta E_0}{k_B T}\right) \quad (3)$$

and

$$\Delta E_0 = \frac{e(V_{G1} - V_{G2})}{\eta}, \quad (4)$$

where ΔE_0 is the activation energy of the circuit. Integrating Eq. (3) with respect to time, we obtain

$$\int_0^{t_1} \left(\frac{I_{D2}}{I_{D1}}\right) dt = \int_0^{t_1} \exp\left(-\frac{\Delta E_0}{k_B T}\right) dt. \quad (5)$$

Because Eq. (5) is an electrical analog of Eq. (1), we can simulate the deterioration of perishables by means of subthreshold MOSFET circuits [1], [2].

With this method, however, activation energy larger than 0.3 eV cannot be obtained because, for such activation energy, current ratio I_{D2}/I_{D1} exceeds 10^3 , making values it difficult to operate both MOSFETs in the subthreshold region. In other words, if the activation energy is set at 0.4 eV or more, current I_{D2} will be extremely small value and less than a MOSFET leak current at low temperature. Therefore, an analog multiplier cannot be used for the large activation energy. To simulate the deterioration process of large activation energy, we constructed a sensor device consisting of both analog and digital circuits, as shown in Fig. 1. The analog circuits simulate Eq. (3) with a small value ΔE_0 of activation energy, and the digital circuits double (and quadruple) the activation energy value and calculates Eq. (5) with the doubled (quadrupled) activation energy. With this construction, we can obtain large activation energy of 0.7 eV

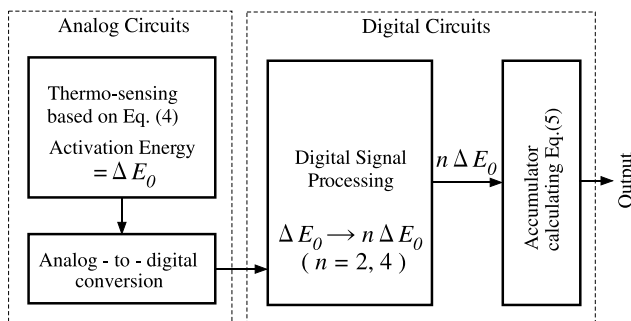


Fig. 1 Construction of proposed sensor device.

or more, as shown in the following sections. This enables us to simulate the deterioration of most perishables such as farm, marine, dairy products, sake and wine, and medical supplies.

3. Sensor Construction with Subthreshold CMOS Circuits

Figure 2 shows a block diagram of the sensor we proposed. The thermosensor and the translinear divider are operated in the subthreshold region and produce an output current I_{OUT} given by Eq. (3), thereby imitating rate equation for deterioration. Activation energy ΔE_0 of the circuit can be controlled by adjusting the difference between two bias voltages V_{G1} and V_{G2} . The current-controlled oscillator (CCO) accepts current I_{OUT} and produces oscillation pulses with a frequency f proportional to I_{OUT} . The digital counter records the number of the pulses at intervals of a short time Δt_s to produce counting output $P(\Delta E_0)$, which is proportional to frequency f . To simulate the deterioration process for large values of activation energy, the counting output is raised to a higher (n th) power by the digital multiplier and is stored in the accumulator. The output of the accumulator is an electrical analog of Eq. (1) with activation energy $\Delta E_0 = n\Delta E_0$. To achieve high portability, we adopt the use of a button-sized battery with a nominal voltage of 1.5 V. Therefore, in the simulation, the supply voltage is set at 1.5 V. The details of each circuit are as follows.

3.1 Thermosensor and Translinear Divider

Figure 3 shows the thermosensor and translinear divider circuits used for simulating the rate equation for deterioration. Given the two input gate-source voltages V_{G1} and V_{G2} , the thermosensor MOSFETs (M5 and M6) produce the subthreshold currents I_{D1} and I_{D2} given by Eq. (4). The translinear divider accepts these currents through current mirrors and produces output current I_{OUT} . In this circuit, the gate-source voltages (V_1 through V_4) for the four MOSFETs (M1 through M4) form a closed loop, so we find that

$$V_1 - V_2 + V_3 - V_4 = 0. \quad (6)$$

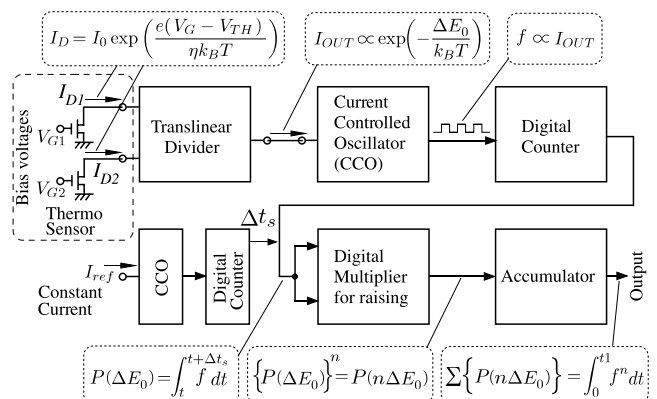


Fig. 2 Detailed block diagram of the sensor device.

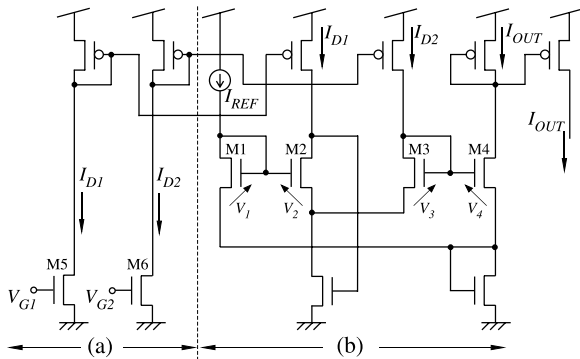


Fig. 3 Circuit configuration of (a) thermosensor circuit and (b) translinear divider circuit, consisting of MOSFETs operated in the subthreshold region. I_{REF} is a constant current independent of temperature. The activation energy of the circuit can be controlled by adjusting $V_{G1} - V_{G2}$.

Based on the translinear principle (see [5], [6] for details), we obtain

$$I_{REF} I_{D2} = I_{D1} I_{OUT}, \quad (7)$$

where I_{REF} is a temperature-independent reference current for the translinear divider. The output current is given by

$$\begin{aligned} I_{OUT} &= I_{REF} \frac{I_{D2}}{I_{D1}} \\ &= I_{REF} \exp\left(-\frac{e(V_{G1} - V_{G2})}{\eta k_B T}\right) \\ &= I_{REF} \exp\left(-\frac{\Delta E_0}{k_B T}\right), \end{aligned} \quad (8)$$

where

$$\Delta E_0 = \frac{e(V_{G1} - V_{G2})}{\eta}. \quad (9)$$

Therefore, the output current can simulate the rate equation Eq. (1) of deterioration. Activation energy ΔE_0 of the circuit can be controlled by adjusting the difference between two bias voltages V_{G1} and V_{G2} .

3.2 Current Controlled Oscillator (CCO)

The current controlled oscillator (CCO) is used for producing the oscillation pulses proportional to the output current of the translinear divider I_{OUT} . Figure 4 shows the CCO consisting of inverters connected in a ring. The oscillation frequency depends on applied current I_{OUT} . Oscillation frequency f is given by

$$f = \frac{1}{2mt_p} = \frac{I_{REF}}{2mC_L V_{dd}} \exp\left(-\frac{\Delta E_0}{k_B T}\right), \quad (10)$$

where m is the number of inverters in the oscillator, t_p is the propagation delay of the inverter, C_L is the load capacitance for each inverter. Since the voltage of button-sized batteries has little temperature dependence, the temperature dependence of supply voltage V_{dd} can be ignored. Oscillation frequency f depends on only temperature and activation energy. Therefore, oscillation frequency f changes in proportion to current I_{OUT} of the translinear divider.

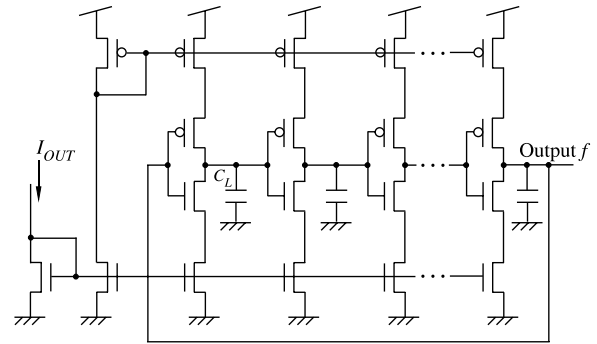


Fig. 4 Current controlled oscillator consisting of inverters connected in a ring. Oscillation frequency f is proportional to input current I_{OUT} .

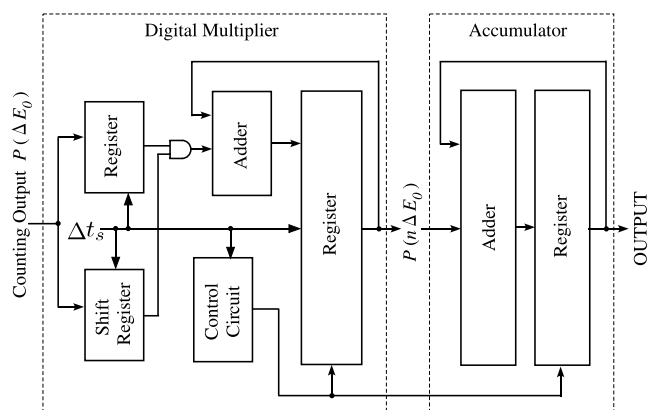


Fig. 5 Flow chart of the digital processing; serial multiplication, and accumulation.

3.3 Digital Counter

The digital counter consists of D flip-flops and counts the number of the CCO oscillation pulses at short time intervals of Δt_s . The counting output $P(\Delta E_0)$ at Δt_s intervals is expressed by

$$P(\Delta E_0) = \int_t^{t+\Delta t_s} f dt. \quad (11)$$

From this, we can calculate the degree of deterioration.

3.4 Digital Multiplier and Accumulator

To simulate the deterioration of perishables for large activation energy, the counting output is raised to a higher (n)th power by a digital multiplier and stored in an accumulator at Δt_s intervals (we set n to 2 or 4). Figure 5 shows the flow chart of this processing; the multiplication is performed in a serial manner with registers and an adder. The output of the multiplier at Δt_s intervals is given by

$$\text{multiplier output} = \left(\int_t^{t+\Delta t_s} f dt \right)^n. \quad (12)$$

On condition that the temperature (frequency f) is almost

constant during short time Δt_s (this is true for Δt_s of a few seconds or minutes), the equation can be written as

$$\begin{aligned} \left(\int_t^{t+\Delta t_s} f dt \right)^n &= \int_t^{t+\Delta t_s} f^n dt \\ &= \left(\frac{I_{REF}}{2mC_L V_{dd}} \right)^n \int_t^{\Delta t_s} \exp\left(-\frac{n\Delta E_0}{k_B T}\right) dt. \end{aligned} \quad (13)$$

In this way, activation energy can be increased to $n\Delta E_0$. The output of the accumulator at time $t1$ is

$$\begin{aligned} \text{accumulator output} \\ &= \left(\frac{I_{REF}}{2mC_L V_{dd}} \right)^n \int_0^{t1} \exp\left(-\frac{n\Delta E_0}{k_B T}\right) dt. \end{aligned} \quad (14)$$

This is analogous to Eq. (1); therefore we can simulate the process of deterioration with large values of activation energy.

Short time interval Δt_s is controlled by the second CCO and the counter shown in Fig. 2. It can be set at an appropriate value (a several seconds or minutes) by adjusting the temperature-independent controlling current I_{ref} for the CCO. The oscillation frequency of the CCO is given by

$$f_s = \frac{I_{ref}}{2mC_L V_{dd}}. \quad (15)$$

The digital counter accepts the oscillation pulses and produces the control signal at intervals of time $\Delta t_s (= 1/f_s)$.

4. Sensor Operation and Simulation Results

We confirmed the operation of the sensor device by a SPICE circuit simulator with a set of 0.35- μm CMOS parameters and a 1.5-V power supply (nominal voltage of dry manganese batteries). Simulations showed that the power consumption of the circuit was only 5 μW at 100°C. This shows that the sensor can work for a year or more with a button-sized battery.

Figure 6 shows the output current I_{OUT} of the translinear divider as a function of temperature, simulated with bias-voltage difference $V_{G1} - V_{G2}$ as a parameter. In simulations, V_{G1} was set to 500 mV, and V_{G2} was changed from 210 mV to 430 mV. Reference current I_{REF} was set to 500 nA. As expected from Eq. (8), output current I_{OUT} was an exponential function of the reciprocal of temperature. The value of I_{OUT} activation energy ΔE_0 was 40 meV for $V_{G1} - V_{G2} = 72.5$ mV and 170 meV for $V_{G1} - V_{G2} = 290$ mV.

Figure 7 shows the output waveform of the CCO, simulated with I_{OUT} activation energy $\Delta E_0 = 170$ meV. The frequency of oscillation was increased with rising temperatures.

Figure 8 shows the oscillation frequency as a function of temperature with I_{OUT} activation energy ΔE_0 as a parameter. The frequency is approximately proportional to output current I_{OUT} of the translinear divider. The oscillation output is applied to the counter, and the counted data is sent to the multiplier at intervals of short time Δt_s .

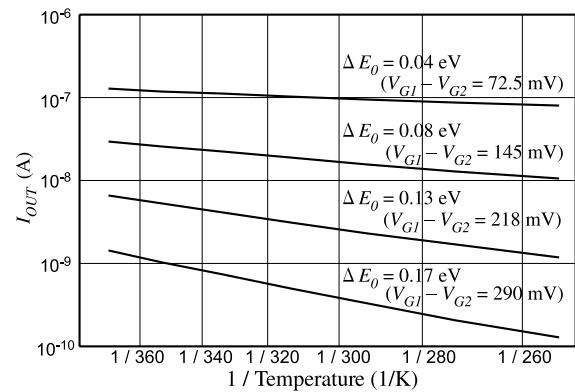


Fig. 6 Output current I_{OUT} of the translinear divider as a function of temperature, simulated for different values of $V_{G1} - V_{G2}$ and $I_{REF} = 500$ nA. The horizontal axis shows the reciprocal of temperature. Output current I_{OUT} is an exponential function of the reciprocal of temperature. ΔE_0 is the activation energy of I_{OUT} .

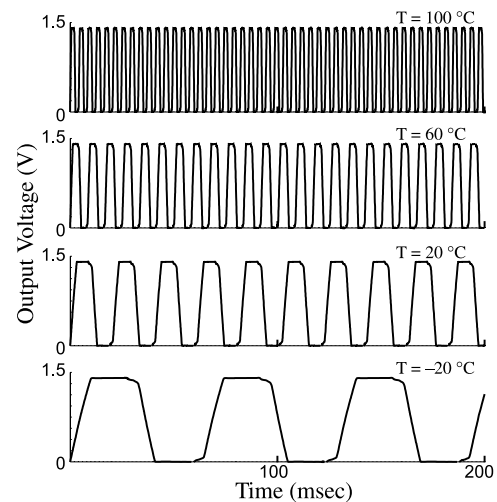


Fig. 7 Output waveforms of the CCO simulated for various temperatures.

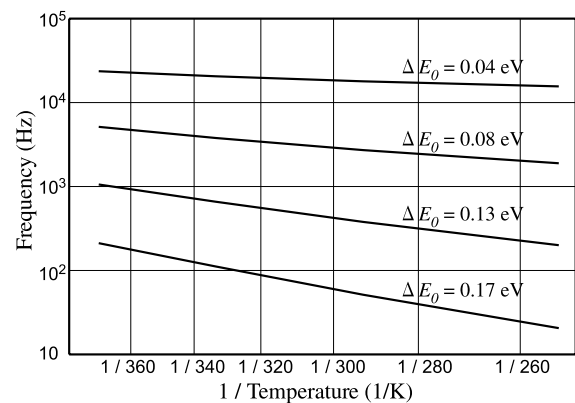


Fig. 8 Oscillation frequency of the CCO at temperatures from -20 to 100°C . ΔE_0 is I_{OUT} activation energy.

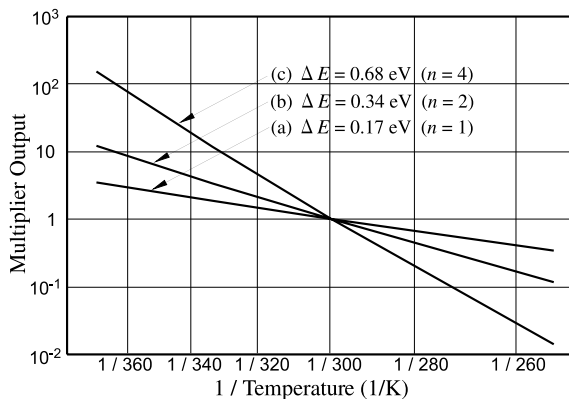


Fig. 9 Multiplier output as a function of temperature, simulated for I_{OUT} activation energy $\Delta E_0 = 0.17$ eV. Plotted for raising factors $n = 1$ (line (a)), $n = 2$ (line (b)), and $n = 4$ (line (c)), and normalized to the value at 300 K. A wide range of total activation energy ΔE can be achieved by adjusting $V_{G1} - V_{G2}$ and raising factor n .

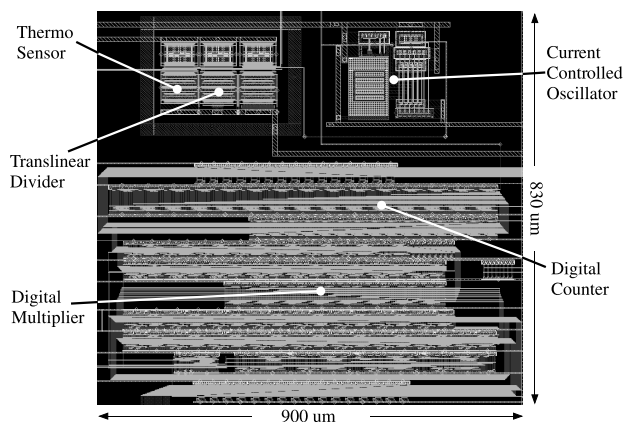


Fig. 10 Layout pattern of the sensor device, designed with $0.35\text{-}\mu\text{m}$, 2-poly, 5-metal CMOS process parameters. The area is $900\text{ }\mu\text{m} \times 830\text{ }\mu\text{m}$, excluding I/O pads and connections.

Figure 9 shows the output of the multiplier (the input for the accumulator) as a function of temperature. This is a result simulated for I_{OUT} activation energy $\Delta E_0 = 0.17$ eV, with raising factors $n = 1$ (line(a)), $n = 2$ (line(b)), and $n = 4$ (line (c)); each output is normalized to the value at 300 K. A wide range of total activation energy (0.1 eV $< \Delta E < 0.7$ eV) can be achieved by adjusting bias voltage $V_{G1} - V_{G2}$ and raising factor n .

Figure 10 shows the chip layout of the sensor device designed with $0.35\text{ }\mu\text{m}$, 2-poly, 5-metal CMOS process parameters. The area including both analog and digital circuit blocks is $900 \times 830\text{ }\mu\text{m}$, excluding I/O pads and connections.

5. Conclusion

A CMOS watchdog sensor circuit for product quality guarantees that dynamically monitors the subthreshold current of a MOSFET was developed. Its operation principle was confirmed with SPICE simulations. The power consumption of the sensor was only $5\text{ }\mu\text{W}$ at 100°C . The button-sized

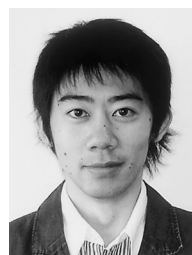
battery with 35 mAh ensures that the circuit works for about 1.2 years. A wide range of activation energy can be achieved by adjusting $V_{G1} - V_{G2}$ of the translinear divider and raising factor by digital multiplier. This enables us to simulate the deterioration of most perishables such as farm, marine, dairy products, sake and wine, and medical supplies.

Acknowledgments

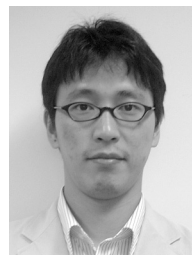
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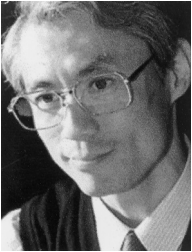


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