ISPACS 2006

2006 International Symposium on Intelligent Signal
Processing and Communication Systems (ISPACS2006)
Yonago Convention Center, Tottori, Japan

# Critical Temperature Switch : A Highly Sensitive Thermosensing Device Consisting of Subthreshold MOSFET Circuits

Atsushi Hagiwara, Tetsuya Hirose, Tetsuya Asai, and Yoshihito Amemiya
Department of Electrical Engineering, Hokkaido University
Kita 14, Nishi 9, Kita-ku, Sapporo 060-0814, Japan

*Abstract* — **A thermosensing circuit that changes its internal state steeply at a critical temperature is proposed. The device makes use of the transition of a MOSFET resistor from strong-inversion operation to weak-inversion or subthreshold operation. The temperature for the transition can be set to a desired value by adjusting the parameters of MOSFETs in the device. The device can be made with a standard CMOS process and can be used as over-temperature and over-current protectors for LSI circuits.**

## I. INTRODUCTION

Safe and stable operation of electrical apparatus is one of the most important matters that require attention. To ensure the stable operation of electrical apparatus, thermally sensitive resistors, or thermistors, are widely used to measure the temperature of the apparatus and detect an undesirable, dangerous increase in temperature [1]. Especially, the positive temperature coefficient (PTC) thermistor is widely used for this purpose because it exhibits a sharp change in resistance at a threshold temperature and is suitable for over-temperature sensing. Therefore, PTC thermistors are often used as overheating detectors, over-current protectors, and temperature-compensation devices. The sharp change in their resistance is caused by the phase transition of conductive ceramics.

However, because PTC thermistors is made of ceramics, they are incompatible with silicon ICs. In addition, it is difficult to set the threshold temperature in a wide range. In this work, we propose a CMOS temperature-sensing device that shows a sharp transition that is similar to that of PTC thermistors. This device----we call it the *critical temperature switch* (CTS) circuit----uses the temperature-sensitive characteristics of MOSFETs operated in the subthreshold region. The CTS circuit is free from the limitation that is inevitable for PTC thermistors.

## II. CTS CIRCUIT

Figure 1 shows our CTS circuit. It is based on the $\beta$-multiplier self-biasing circuit [4] and uses a MOSFET resistor M7 instead of an ordinary resistor. We operate all of MOSFETs in this circuit in a subthreshold region except for M7. The current mirror consisting of M1 and M2 makes currents $I_1$ and $I_2$ equal to each other. The circuit shows switching operation such that node voltage $V_b$ changes drastically from a high value to a low one at threshold temperature $T_C$. The detailed operation is discussed below.

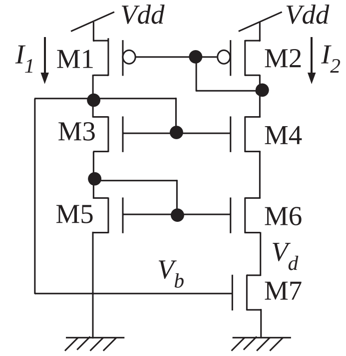

Fig. 1 Critical temperature switch (CTS) circuit

### A. Circuit Operation

The circuit operation can be analyzed using the transfer curves for left branch (M2-M4-M6-M7) and right one (M1-M3-M5). Current $I_1$ in the left branch flows through M3 and M5 and generates voltage $V_b$, and current $I_2$ in the right branch is controlled by voltage $V_b$. Because $I_1$ and $I_2$ are equal to each other, we can find the operating point of the circuit by observing the intersection of two transfer curves, or $I_1$-$V_b$ curve and $I_2$-$V_b$ curve, of the circuit. This is illustrated in Figs. 2(a) –2(c), each of which plots $I_1$ and $I_2$ as a function of $V_b$ for different temperatures. At low temperatures, the two curves intersect with each other at two points A and B, as shown in Fig. 2(a). Point A is a stable operating point, and B is an unstable point. If initial value of $V_b$ is higher than the voltage for point B, the circuit will settle down to stable point A. In contrast, if initial value is lower than the voltage for B, the current, therefore voltage $V_b$, of the circuit decreased to 0. Therefore, the circuit has two possible operating point --- one is point A and the other is $I_1 = I_2 = 0$ (therefore $V_b = 0$) --- according to its initial condition.

0-7803-9733-9/06/$20.00©2006 IEEE

As temperature increases, intersections A and B approach each other because the temperature characteristics of the two transfer curves are different from each other (Fig. 2(b)). At the critical (or threshold) temperature, intersections A and B overlap each other. At higher temperatures, the two curves have no intersection as shown in Fig. 2(c). Therefore the circuit operates at the zero point ($I_1 = I_2 = 0$, $V_b = 0$). The CTS circuit shows the switching operation at threshold temperature because of the transition of the operating point from A to zero.

### *B. Theoretical Analysis of Threshold Temperature*

The threshold temperature $T_C$ can be calculated theoretically. The CTS circuit we propose uses the characteristic of MOSFET operated in a subthreshold region. The subthreshold drain current $I_d$ through a MOSFET is an exponential function of gate-source voltage $V_{gs}$ and is given by

$$I_d = K_M I_0 \exp\left(\frac{V_{gs} - V_{th}}{\eta V_T}\right), \tag{1}$$

where $K_M$ is the aspect ratio of the MOSFET, $I_0$ is a process-dependent parameter, $V_T$ (= $k_B T/q$) is the thermal voltage, $k_B$ is the Boltzmann constant, $T$ is absolute temperature, $q$ is the elementary charge, $\eta$ is the subthreshold slope factor, and $V_{th}$ is the threshold voltage of the MOSFET [2], [3]. According to Eq. (1), the subthreshold drain current changes sensitively to the absolute temperature $T$.

In the CTS circuit in Fig.1, gate-source voltage $V_{GS,M5}$ in transistor M5 must be equal to the sum of gate-source voltage $V_{GS,M6}$ in M6 and drain-source voltage $V_d$ in M7, or

$$V_{GS,M5} = V_{GS,M6} + V_d. \tag{2}$$

Because the currents through transistors M5 and M6 are equal to each other, Eq. (2) can be rewritten as

$$V_d = \eta V_T \ln(K), \tag{3}$$

where $K$ is the ratio between aspect ratios $K_{M5}$ and $K_{M6}$ in M5 and M6: that is, $K = K_{M6}/K_{M5}$. Since transistors M3 and M5 are connected in a cascode configuration, gate voltage $V_b$ of M7 is higher than the threshold voltage of M7. Therefore, transistor M7 operates in the strong inversion. At this time, current $I$ and gate voltage $V_b$ in M7 are given by

$$\begin{aligned} I &= \beta(V_b - V_{th})V_d \\ &= \beta(V_b - V_{th})\eta V_T \ln(K) \end{aligned}, \tag{4}$$

and

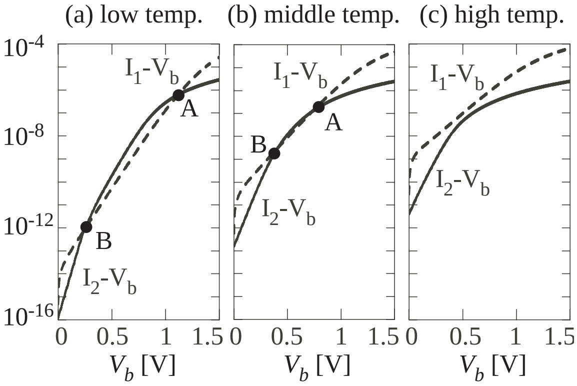

Fig. 2 Two transfer curves ($I_1$-$V_b$ and $I_2$-$V_b$) curves at different temperature.

$$V_b = 2V_{th} + 2\eta V_T \ln\left(\frac{I}{I_0}\right), \tag{5}$$

where $\beta$ is the current gain factor. From these equations, current $I$ and voltage $V_b$ in the circuit are determined by each other.

The temperature dependence of threshold voltage $V_{th}$ is expressed as

$$V_{th} = V_{th0} - \kappa T, \tag{6}$$

where $V_{th0}$ is the threshold voltage in absolute zero temperature, and $\kappa$ is the temperature coefficient of the threshold voltage [2]. From Eqs. (4), (5), and (6), we find that the slope of voltage $V_b$ with temperature is given by

$$\frac{\partial V_b}{\partial T} = \frac{\alpha}{\beta\eta V_T \ln(K) - \dfrac{I_0}{2\eta V_T}\exp\left(\dfrac{V_b - 2V_{th}}{2\eta V_T}\right)}, \tag{7}$$

$$\begin{aligned} \alpha = {} & \left(1 + \frac{4\kappa T - (V_b - 2V_{th})}{2\eta V_T}\right)\frac{I_0}{2T}\exp\left(\frac{V_b - 2V_{th}}{2\eta V_T}\right) \\ & + \left(\frac{V_b - V_{th}}{2T} - \kappa\right)\beta\eta V_T \ln(K) \end{aligned}. \tag{8}$$

In the standard CMOS parameters, α is negative and the denominator in Eq. (7) is positive. Therefore, the slope of $V_b$ decreases with temperature. The denominator in Eq. (7) also decreases with temperature. At the threshold temperature, the denominator becomes to be 0 and the slope of voltage $V_b$ becomes negative infinity. This phenomenon produces the

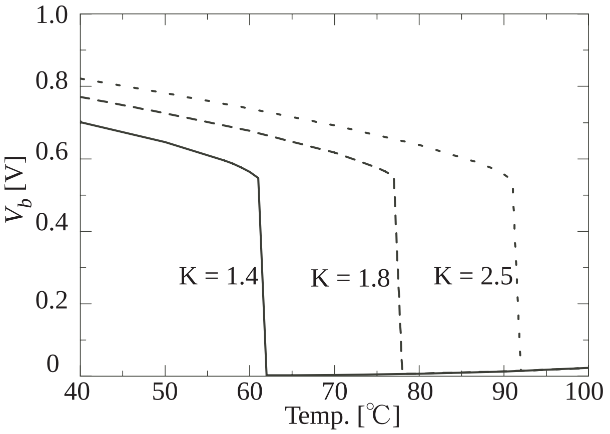

Fig. 3 Voltage $V_b$ as a function of temperature with $K$ as a parameter. Threshold temperature can be set by changing $K$.

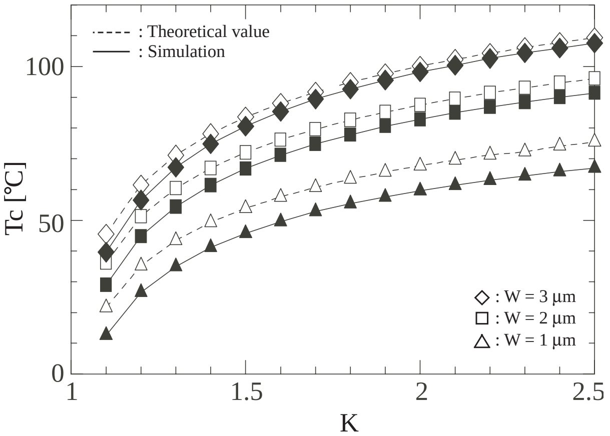

Fig. 4 Threshold temperature $T_c$ as a function of $K$, with the channel width as a parameter. $T_c$ can be set at a wide range from 0 °C to 110 °C.

sharp change in $V_b$ and a switching operation of the circuit. The threshold condition of the circuit is given by

$$V_b = V_{th} + 2\eta V_T, \tag{9}$$

From this condition, threshold temperature $T_c$ can be given by

$$T_c = \frac{V_{th0}}{2\eta \frac{k_B}{q}\left\{1 - \ln\left(2M\frac{\eta^2}{\eta - 1}\ln(K)\right)\right\} + \kappa}, \tag{10}$$

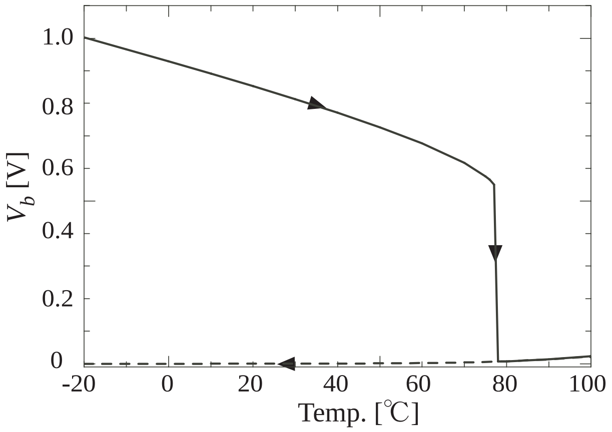

Fig. 5 Different behaviors for $V_b$ with decreasing temperature after increasing temperature. The CTS circuit has two possible operating points below threshold temperature.

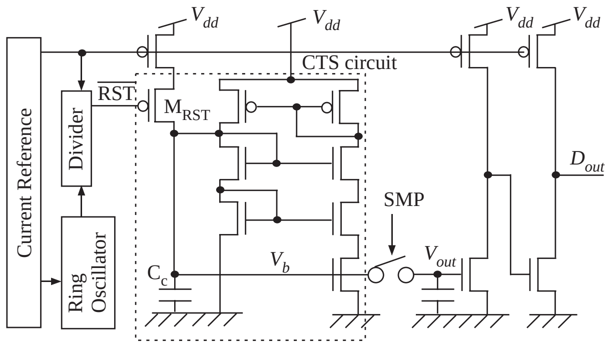

Fig. 6 CTS circuit with a resetting subcircuit.

where $M$ is the ratio of $\beta$ in M5 and M7 ($M = \beta_{M5} / \beta_{M7}$). Threshold temperature $T_c$ can be controlled by changing the circuit parameters.

### C. *Simulation Results*

We confirmed the operation of the CTS circuit by SPICE simulation with a set of 0.35-μm CMOS parameters and a 1.5-V power supply. Figure 3 shows the change of $V_b$ as a function of increasing temperature with three different parameters $K$. The voltage $V_b$ decreases as temperature increases and drops suddenly at the threshold temperature. Threshold temperature $T_c$ can be set by changing the parameter $K$. Figure 4 shows threshold temperature as a function of the value of $K$, with the channel width as a parameter. Theoretical threshold temperatures are also plotted. These results show that threshold temperature $T_c$ can be set in a wide range from 0 °C to 110 °C by changing circuit parameters.

## III. Reset Circuit

The CTS circuit performs a switching operation by monitoring the voltage $V_b$, which change from a higher voltage (strong inversion bias condition for M7) to a lower voltage (subthreshold bias condition for M7) with temperature. However, the CTS circuit shows different behaviors when it operates with decreasing temperature after increasing temperature. This phenomenon is due to an unstable operating point B (see Fig.2). When the circuit operates at temperatures higher than $T_C$, voltage $V_b$ drops down to a lower voltage. However, voltage $V_b$, once dropped, does not return to a high voltage even if temperature decreases again below the threshold temperature because $V_b$ is smaller than the unstable point B. This characteristic of the CTS circuit is shown in Fig.5. Because of the unstable operating point B, voltage $V_b$ has two possible operating points below threshold temperature $T_c$.

To cancel the effect of the unstable point B, we used a subcircuit for resetting $V_b$ periodically to a high voltage (higher than unstable point voltage). With this resetting, M7 can be returned to a strong-inversion region at temperatures under the threshold temperature. Figure 6 shows the total system including the resetting subcircuit. The subcircuit consists of a ring oscillator, a frequency divider, and a resetting transistor $M_{RST}$ connected to the CTS circuit. We used a nanoampere-current source [5], and by this current the ring oscillator is driven and produces a square wave. The frequency divider accepts the square wave and produces a resetting pulse (RST) and sampling pulse (SMP). Transistor $M_{RST}$ accepts the resetting pulse and sets $V_b$ to a high voltage periodically, thereby setting M7 to a strong-inversion region periodically. The voltage $V_b$ is sampled periodically with a sampling pulse (SMP) and is retrieved as an output voltage $V_{out}$ on the capacitance $C_c$, and then it is output as a digital signal ($D_{out}$) after through a current-source inverter and a current-limited inverter.

We confirmed the resetting operation by SPICE simulation. A CTS circuit with a threshold temperature of 75 °C was used, and temperature was assumed to be 70 °C. At this temperature, the CTS circuit should produce a high-voltage output but, because of the effect of unstable point B, produces a low-voltage output if the initial output was low. This is corrected by resetting. The results are shown in Fig. 7. The initial voltage of $V_b$ was set at 0 V; therefore an initial output was 0, an incorrect output for a temperature (70 °C) lower than the CTS threshold (75 °C). After the first resetting pulse was applied to the CTS, voltage $V_b$ set above the unstable point voltage, and the voltage $V_b$ operated at stable point. At the second resetting pulse, the CTS produced a correct voltage output and, after that, maintained its correct output.

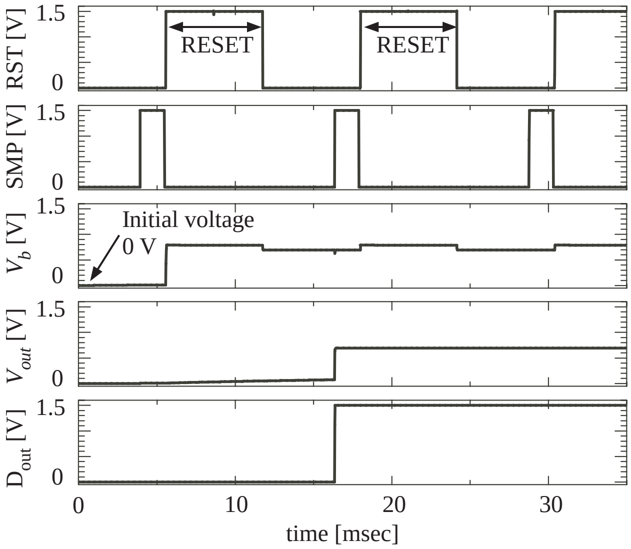

Fig. 7 Reset operation of the circuit. The initial voltage of $V_b$ is set at 0 V. Simulated for temperature of 70 °C (the threshold temperature of the CTS circuit is 75 °C).

## IV. Conclusion

A critical temperature switch (CTS) circuit consisting of subthreshold MOSFET circuits was developed. It changes its state drastically at a threshold temperature by making use of the transition in a MOS resistor from strong-inversion to subthreshold operation. The threshold temperature can be set to a desired value by adjusting the MOSFETs parameters in the circuit. The device can be made with a standard CMOS process and be used for over-temperature protecting for LSI circuits.

## References

[1] J. Scholz, T. Ricolfi, Sensors Vol.4 Thermal Sensors, VCH, 1990.

[2] Y. Taur, T.H. Ning, Fundamentaks of Modern VLSI Devices, Cambridge University Press., 2002.

[3] P.R. Gray and R.G. Mayer, Analysis and Design of ANALOG INTEGRATED CIRCUITS, third ed., Wiley & Sons, 1993.

[4] R. Baker, H. Li, D. Boyce, CMOS Circuit Design, Layout, and Simulation, IEEE Press., 1997.

[5] H.J. Oguey, D. Aebischer, CMOS Current Reference Without Resistance, IEEE JOURNAL OF SOLID-STATE CIRCUIT, 1997.