CMOS phase-shift oscillator using the conduction of heat

Takaaki Hirai†, Tetsuya Asai and Yoshihito Amemiya

Department of Electrical Engineering, Hokkaido University
Kita 14, Nishi 9, Kita-ku, Sapporo, 060-0814, Japan
Phone:+81-11-706-7147, Fax:+81-11-706-7890 † E-mail: hirai@sapiens-ei.eng.hokudai.ac.jp

Abstract We propose a CMOS phase-shift oscillator that makes use of a phase shift in the conduction of heat. The oscillator consists of an inverting amplifier and a feedback thermal filter that are integrated monolithically on a silicon chip. The thermal filter consists of a polysilicon heater and a MOSFET thermosensor that are separated from each other by a heat-conducting SiO2 layer. It accepts the output of the inverting amplifier, produces a phase shift due to heat conduction, and returns a 180 °-shifted feedback signal to the amplifier. The oscillator can be expected to produce oscillation at a specific frequency determined by the dimensions of the filter and the thermal conductivity and specific heat of Si and SiO2.

1. Introduction

In conventional integrated circuits, signals are represented, transmitted, and processed by using voltage or current or both. In this paper, we propose using heat as a medium of signal transmission. Integrated circuits that make use of a conduction of heat will open a new field of signal-processing applications. For example, heat can travel through an insulator, and therefore signals can be exchanged between two circuits that are electrically isolated from each another. Another example is making use of a delay in heat conduction. A heat conduction system has a great similarity to an electrical transmission line, so we can make a heat conduction system as a delay circuit and a low-pass filter for analog signals.

In the following sections, we propose and design a phase-shift oscillator that uses a thermal low-pass filter consisting of a heat conduction system. Because heat conduction systems have a large time constant, we can make low-frequency oscillators without large-capacitance and high-resistance elements. Section 2 shows that the mathematical equation for the conduction of heat is analogous to that for a RC transmission line. A heat conduction system can therefore be used as a low-pass filter. Section 3 proposes a heat conduction device that can be made with CMOS process technology. Section 4 proposes a phase-shift oscillator consisting of a CMOS amplifier and the heat conduction device used as a feedback low-pass filter to produce a phase shift of signals. The operation of the oscillator is confirmed using computer simulation.

2. Phase shifting based on heat conduction

The conduction of heat in a one-dimensional medium, shown in Fig.1(a), can be expresses by partial differential equation

$$c\rho\frac{\partial\theta(x,t)}{\partial t} = \kappa\frac{\partial^2\theta(x,t)}{\partial x^2} \tag{1}$$

where $\theta(x,t)$ is temperature as a function of distance x and time t. Parameters c and ρ are the specific heat and the density per unit length of the medium, and κ is the thermal conductivity of the material of the system. The product $c\rho$ is the thermal capacity per unit length. Equation (1) is analogous to the equation for a RC transmission line shown in Fig.1(b). The transmission line equation is

$$C\frac{\partial V(x,t)}{\partial t} = \frac{1}{R}\frac{\partial^2 V(x,t)}{\partial x^2} \tag{2}$$

where $V(x,\ t)$ is voltage as a function of distance x and time t. Parameters C and R are the capacitance and the resistance per unit length of the transmission line. Equation (1) can be reduced to Eq. (2) by replacing temperature $\theta(x,\ t)$ with voltage $V(x,\ t)$ and the thermal parameters with the electrical parameters (see Table 1). Thus, we can use a heat conduction system as a low-pass filter. We call this filter a thermal filter.

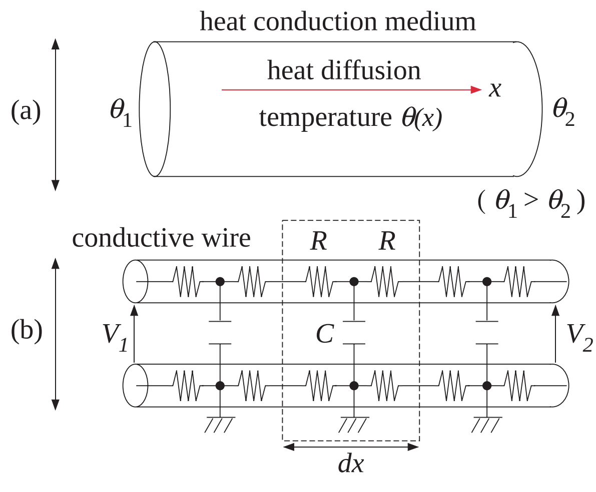

Fig. 1 Heat conduction system and RC transmission line: (a) one-dimensional heat conduction system, and (b) RC transmission line consisting of a pair of conductive wires.

Heat conduction system		RC Transmission line
Temperature	⟷	Voltage
Heat Flow	⟷	Current
Thermal Resistance	⟷	Resistance
Thermal Capacity	⟷	Capacity

Table 1 Analogy between heat conduction system and RC transmission line

Using a thermal filter as a phase shifter can create a new type of phase-shift oscillator. Figure 2 shows the concept of our new oscillator compared with a conventional oscillator that uses a phase shifter consisting of a RC low-pass filter. The thermal filter for our oscillator consists of a heater, a heat conducting region that operates as a phase shifter, and a thermosensor. The sinusoidal signal from the inverting amplifier drives the heater and generates heat signal. The heat signal travels in the heat conducting region to produce a phase shift. The thermosensor accepts the phase-shifted heat signal and produces the corresponding electrical output. The output is returned to the input of the amplifier. The oscillator oscillates at a particular frequency at which the phase shift in the thermal filter is 180 °.

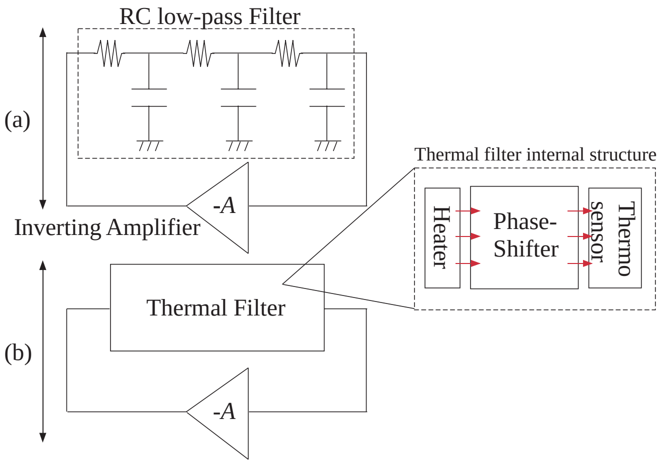

Fig. 2 Phase-shift oscillator consisting of a thermal filter and an inverting amplifier: (a) conventional phase-shift oscillator using a RC low-pass filter as a phase shifter, and (b) our phase-shift oscillator using the thermal filter as a phase shifter.

3. Thermal filter consisting of CMOS devices

We designed the thermal filter that can be monolithically integrated with CMOS devices. Figure 3 shows the structure (the left-end device). An nMOSFET is used as a thermosensor, and the heater is made with the second polysilicon layer. The heat conducting region consists of a SiO2 layer (between the gate polysilicon and the second polysilicon layers), the gate polysilicon layer, and the gate oxide layer. We operate the thermosensor MOSFET in the subthreshold region. The drain current of a subthreshold-operated MOSFETs is sensitive to temperature and increases with temperature, as shown in Fig.4, and therefore can be used as a thermosensor. The heat signal from the heater travels in the heat conducting region to produce a phase shift and reaches the thermosensor MOSFET. The phase-shifted heat signal modulates the drain current of the MOSFET, and the MOSFET produces the corresponding current signal.

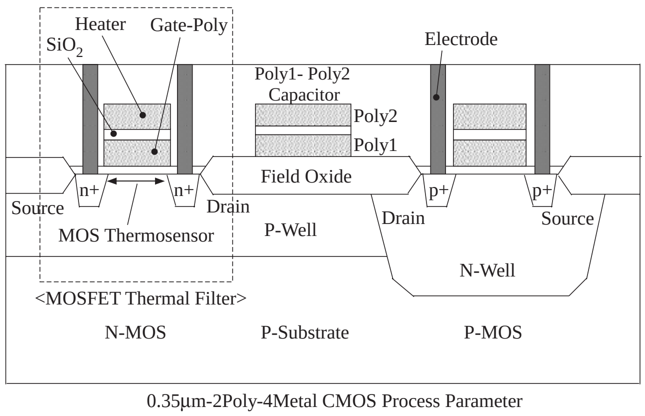

Fig. 3 Thermal filter made with CMOS technology (left-end device)

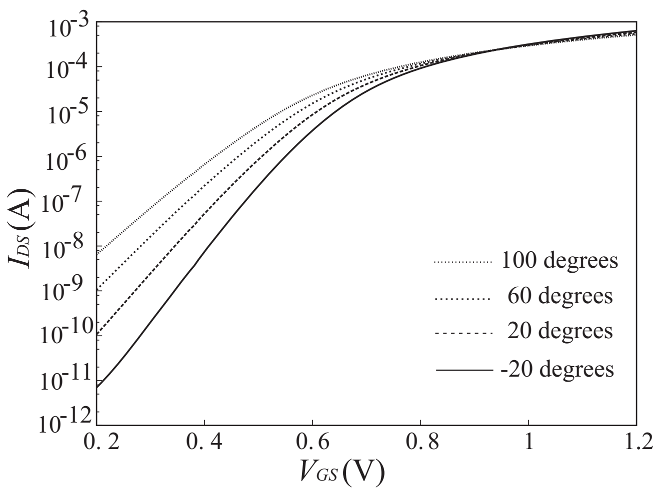

Fig. 4 Drain current of a MOSFET as a function of the gate voltage, with temperature as a parameter.

To simulate the operation of the thermal filter, we made the equivalent circuit for the filter. The flow of heat in the filter is shown in Fig.5. Heat from the heater travels downward through the heat-conducting region (SiO2-poly Si-SiO2) and reach the thermosensor MOSFET. Then the heat is diffused radially into the silicon substrate. An upward conduction of heat is very little because the surface of the filter is covered a thick SiO2 layer, a bad conductor for heat.

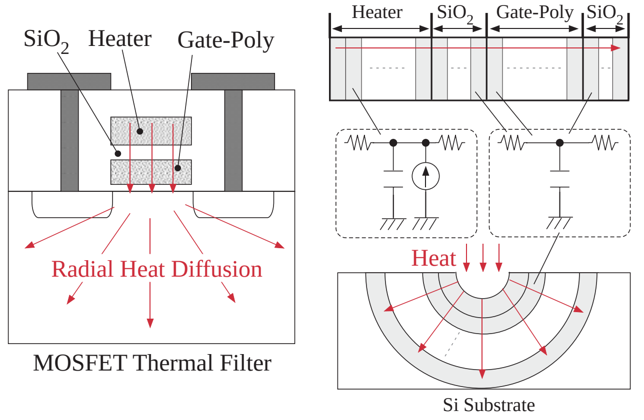

Fig. 5 Flow of heat in the thermal filter.

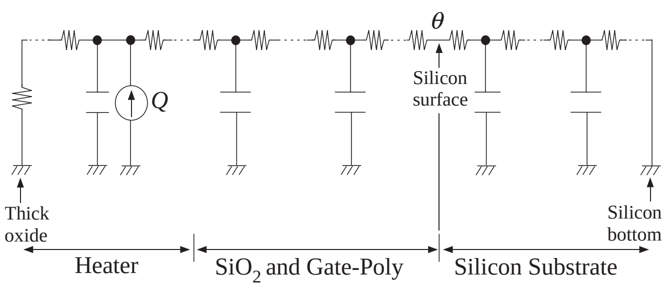

Fig. 6 Small signal equivalent circuit of the thermal filter. Q is electric power dissipated in each subdivided layer in the heater. θ is temperature at the surface of the thermosensor MOSFET

The equivalent circuit for the filter is shown in Fig.6. We subdivided each part of the filter into many thin layers and replaced each layer with an RC circuit. That is, the heater was subdivided into many flat layers, each of which was replaced with a RC low-pass circuit with a current source that represented the generation of heat. The heat-conducting region (SiO2-polySi-SiO2) was also subdivided into many flat layers, each of which was replaced with a RC low-pass circuit. The silicon substrate was subdivided into many hemispherical layers, each of which was replaced with a RC low-pass circuit. The bottom of the substrate was kept at a fixed temperature, so the right end of the equivalent circuit was grounded. The upward conduction of heat was represented with a high resistance connected at the left end of the equivalent circuit.

We designed the thermal filter with a parameter set for 0.35-μm CMOS devices and simulated the frequency response of the thermal filter. The result is shown in Fig.7 plotting the log magnitude and phase shift of θ (θ = temperature of the surface of the thermosensor MOSFET, Q = electric power dissipated in the heater) as a function of frequency.

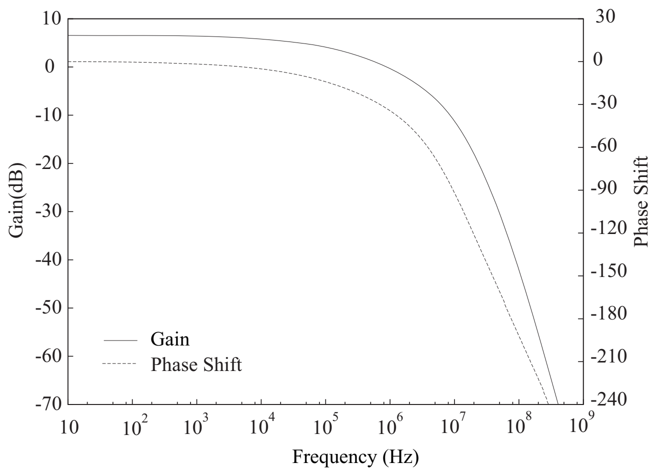

Fig. 7 Frequency response of the thermal filter.

4. Constructing phase-shift oscillator

To construct a phase-shift oscillator, we made a heat-conduction amplifier by combining two thermal filters with a heater-driving circuit and a differential amplifier. Figure 8(a) shows the heater-driving circuit. It accepts a differential input voltage Vin and produces the corresponding output currents $i1$ and $i2$ to drive two thermal filters. The outputs drive the heaters of the thermal filters combined with the differential amplifier shown in Fig.8(b). The thermal filters produce a phase shift in input signals, and the thermosensor MOSFETs produce the corresponding drain currents. The differential amplifier then produces a phase-shifted output voltage $Vout$.

We designed a heat-conduction amplifier with a parameter set for 0.35-μm CMOS devices and simulated its frequency response (the Bode plot for $Vout/Vin$). Figure 9 shows the result. The phase shift in the amplifier is larger than that in the thermal filter alone. This is due to an additional phase shift produced in the differential amplifier shown in Fig.8(b). To our regret, the gain of the heat-conduction amplifier was -9.6 dB at a 180 $^\circ$ phase shift (frequency = 9.33 MHz) because signal attenuation in the thermal filter was larger than we had expected. Therefore, an oscillator was unable to be constructed with a single heat-conduction amplifier.

To solve this problem, we connected three heat-conduction amplifiers into a loop to form a triple-phase oscillator as shown in Fig. 10. The gain of a single amplifier was 17 dB at a 60 °phase shift (frequency = 0.76 MHz), so the triple-phase oscillator was able to oscillate.

5. Operation of the triple-phase oscillator

We simulated the operation of the oscillator. The waveforms of oscillation are shown in Fig.11. The solid line shows the output voltage ($Vout$ in Fig.8(a)) of an amplifier, and the dashed line shows the difference between the channel temperatures of thermosensor MOSFETs in the amplifier. The oscillation frequency was 1.25MHz, and it is lower than expected from the phase-shifting characteristic of the thermal filter. This is caused by an additional phase shift produced in the differential amplifier. We are now developing an improved amplifier that produces no phase shift in this range of frequency. With this amplifier, we will be able to construct a phase-shift oscillator that oscillates at a specific frequency determined only by the phase-shifting characteristic of the thermal filter.

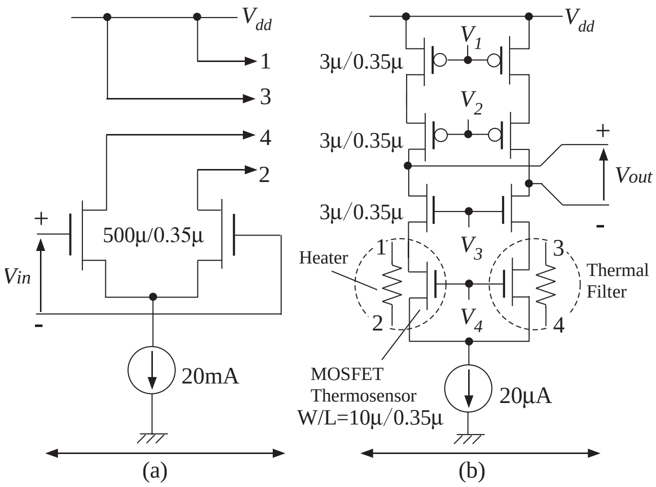

Fig. 8 Heat-conduction amplifier consisting of (a) heater-driving circuit and (b) differential amplifier combined with thermal filters used as phase shifters.

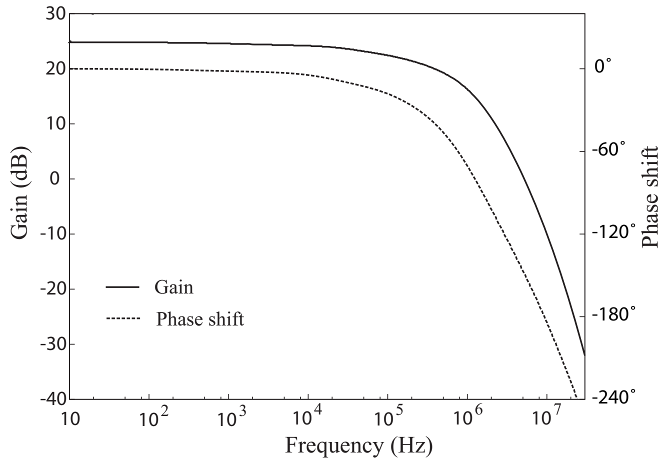

Fig. 9 Frequency response of the heat-conduction amplifier shown in Fig.8. Log magnitude (or gain) and phase shift of $Vout/Vin$ are plotted as functions of frequency. The gain is 17 dB at 60 ° phase shift and -9.6 dB at 180 ° phase shift.

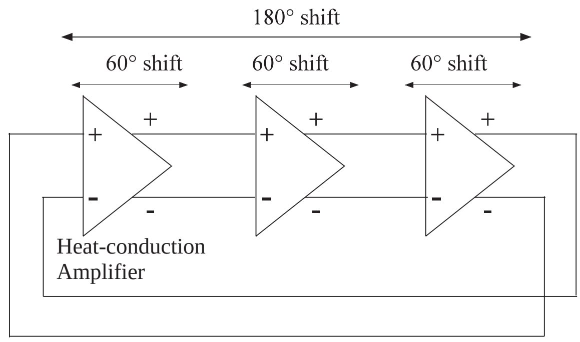

Fig. 10 Triple-phase oscillator consisting of three heat-conducting amplifiers connected into a loop.

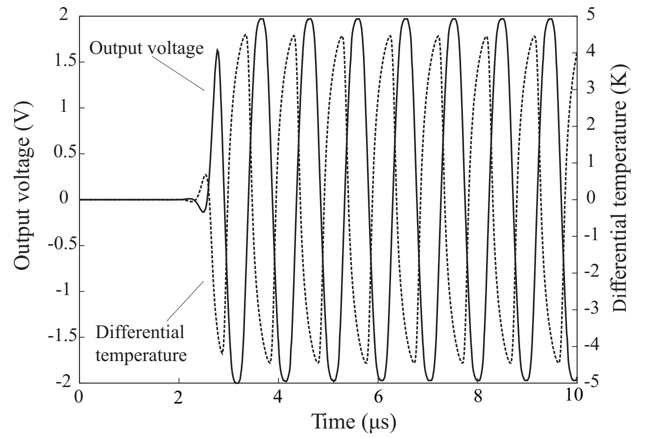

Fig. 11 Oscillation waveforms for differential output voltage and differential temperature of an amplifier in the oscillator.