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A CMOS PHASE-SHIFT OSCILLATOR BASED ON THE CONDUCTION OF HEAT

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A CMOS phase-shift oscillator that uses a phase shift in the conduction of heat is proposed. The oscillator consists of an inverting amplifier and a feedback thermal filter that are integrated on a silicon chip. The thermal filter consists of a polysilicon heater and a MOSFET thermosensor separated from each other by a S_iO_2 heat-conducting layer.[1] An input signal for the filter travels from the heater to the thermosensor through the $S_iO_2$layer in the form of heat. The filter accepts the output of the inverting amplifier, produces a phase shift due to the heat conduction, and returns a 180°-shifted feedback signal to the amplifier. The oscillator produces oscillation at a specific frequency determined by the dimensions of the filter and the thermal conductivity and specific heat of Si and S_iO_2.

Keywords: Heat conduction; phase-shift oscillator; thermo sensor.

1. Introduction

In conventional integrated circuits, signals are represented, transmitted, and processed by using only voltage, current, and occasionally light. However, heat can also be used 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 the use of a delay in heat conduction. A heat conduction system has a great similarity to an electrical RC transmission line, so we can make a heat conduction system as a delay circuit and a low-pass filter for analog signals. In this paper, we present a CMOS phase-shift oscillator that uses a heat conduction system as a filter for 180° phase shifting.

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 presents 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. We confirmed the operation of the oscillator experimentally.

2. Heat Conducting System as a Low-Pass Filter

The conduction of heat in a one-dimensional system, shown in Fig. 1(a), can be expressed 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 t the time. Parameters c and ρ are the specific heat and the density per unit length of the material of the system, and κ is the thermal conductivity of the material. The product $c\rho$ is the thermal capacity per unit volume. Equation (1) is analogous to the equation for a RC transmission line shown in Fig. 1(b). The RC transmission line equation is given by

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

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)

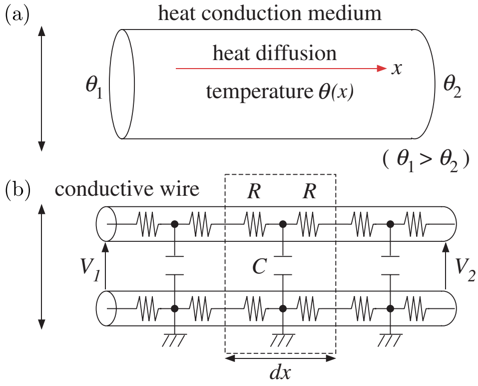


Fig. 1. Heat conduction system and RC transmission line: (a) one-dimensional heat conduction system, and (b) RC transmission line consisting of a pair of conductive wires.

Table 1. Analogy between the heat conduction system and RC transmission line.

Heat conduction system		Transmission wire
Temperature	↔	Voltage
Heat current	↔	Current
Heat resistance	↔	Resistance
Heat capacitance	↔	Capacitance

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".

Using the thermal filter as a phase shifter can create a new type of phase-shift oscillators. Figure 2 shows the concept of our new oscillator compared with a conventional oscillator that uses a phase shifter consisting of an 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 a heat signal. The heat signal travels in the heat conducting region to produce a phase shift. The thermosensor accepts a 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°.

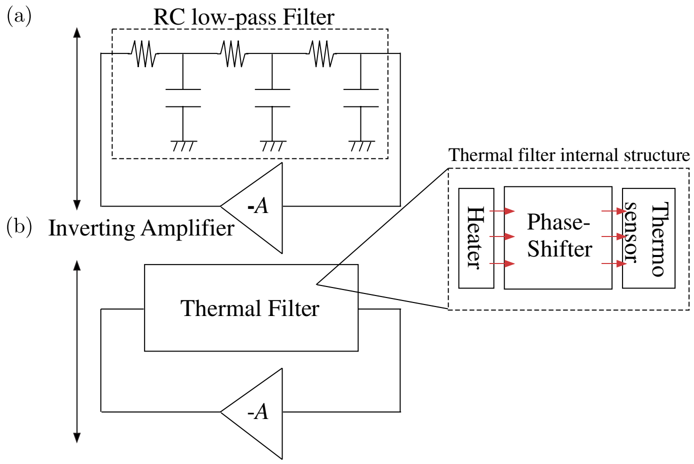


Fig. 2. Phase-shift oscillator consisting of thermal filter and inverting amplifier: (a) conventional phase-shift oscillator using RC low-pass filter as phase shifter, and (b) our phase-shift oscillator using thermal filter as phase shifter.

3. Thermal Filter Made with CMOS Technology

We designed a thermal filter that can be monolithically integrated with CMOS devices. Figure 3 shows the structure (the left-end device) together with other devices, a capacitor and a pMOS FET. An nMOSFET is used as a thermosensor. The heater is made with the second polysilicon (polySi) layer. The heat conducting region consists of a S_iO_2 layer (between the heater and the gate polySi), the gate polySi layer, and a gate oxide layer. We operate the thermosensor MOSFET in the subthreshold region.[2,3] The drain current of a subthreshold-operated MOSFETs is sensitive to temperature and increases with temperature, as shown in Fig. 4, and

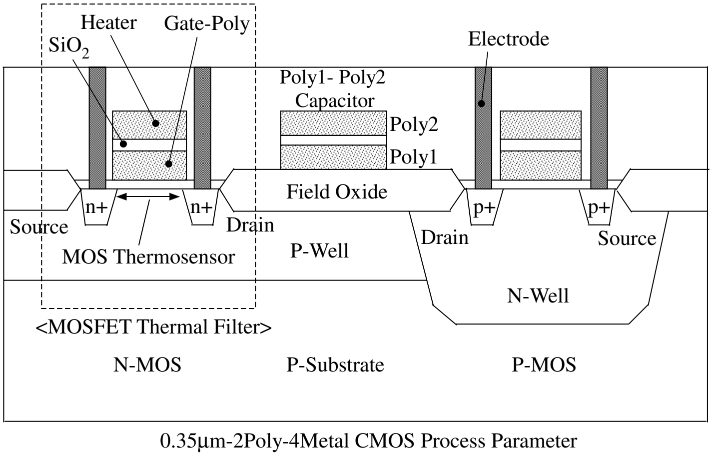


Fig. 3. Thermal filter made with CMOS technology (left-end device).

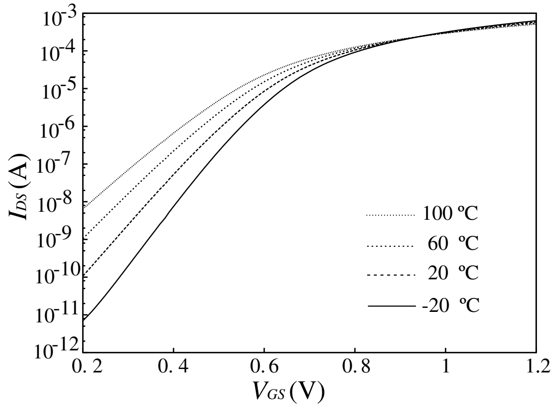


Fig. 4. Drain current of MOSFET as a function of the gate voltage, with temperature as a parameter (SPICE examples with typical 0.35-μm CMOS parameters).

therefore can be used as a thermosensor.[4,5] 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.

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 (S_iO_2-polySi-S_iO_2) and reach the thermosensor nMOSFET. Then the heat is diffused radially into the silicon substrate. An upward conduction of heat from the heater is very little because the surface of the filter is covered with a thick S_iO_2 layer, a poor conductor for heat.

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 an RC low-pass circuit with a current source that represented the generation of heat.

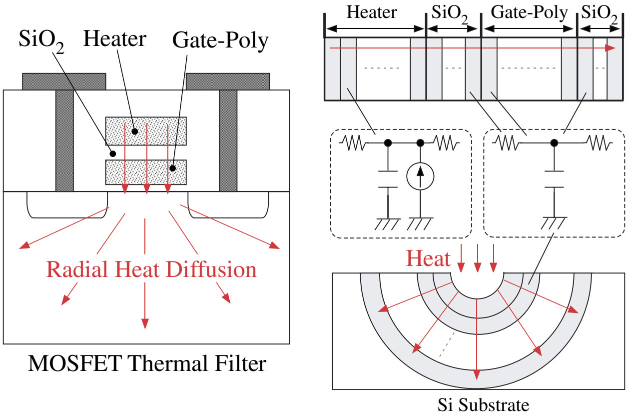


Fig. 5. Flow of heat in thermal filter.

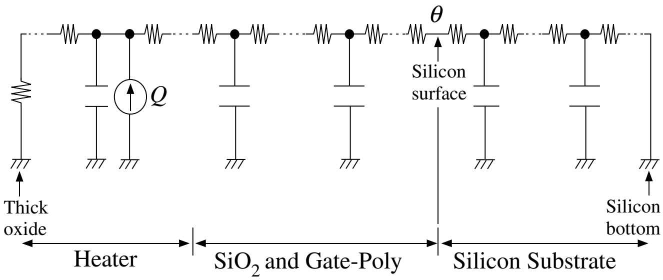


Fig. 6. Small signal equivalent circuit for thermal filter. Q is electric power dissipated in each subdivided layer in heater. θ is temperature at surface of thermosensor MOSFET.

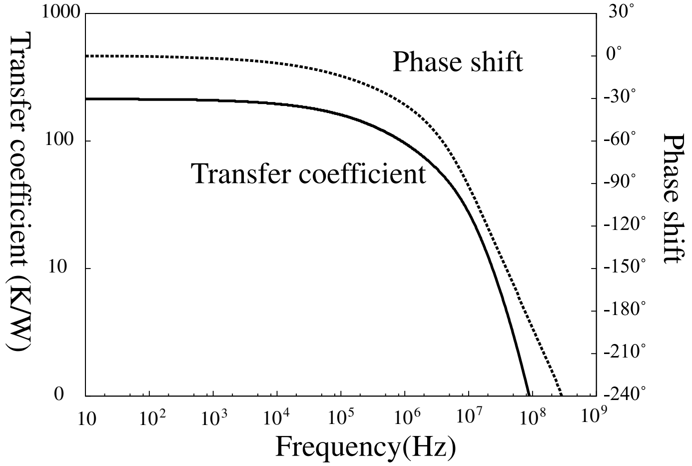


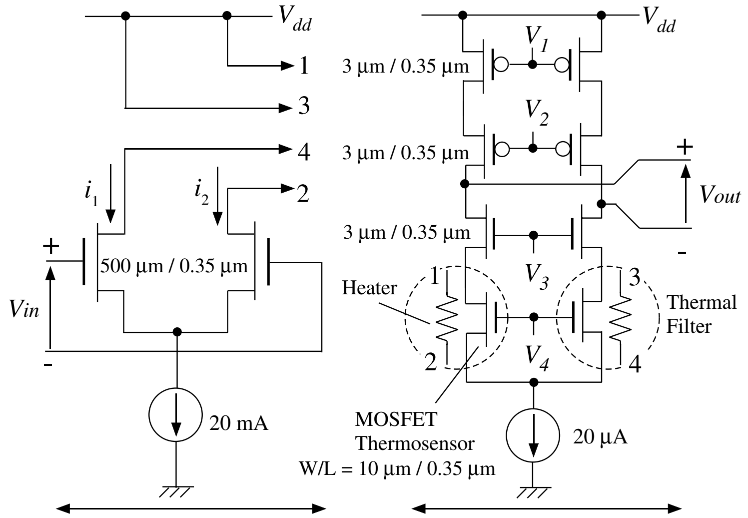
Fig. 7. Simulated frequency response of thermal filter consisting of 0.35-μm CMOS devices (SPICE). Frequency is 4 MHz for 60° phase shift and 68 MHz for 180° shift.

The heat-conducting region (S_iO_2-polySi-S_iO_2) was also subdivided into many flat layers, each of which was replaced with an RC low-pass circuit. The silicon substrate was subdivided into many hemispherical layers, each of which was replaced with an 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 SPICE result is shown in Fig. 7 plotting the log magnitude and phase shift of θ/Q as a function of frequency (θ is the temperature of the surface of the thermosensor MOSFET and Q the electric power dissipated in the heater). The frequency for 60° phase shift was 4 MHz and for 180° phase shift was 68 MHz.

4. Phase-Shift Oscillator with Thermal Filters and its Operation

A phase-shift oscillator is a simple electronic oscillator that generates sine waves. It consists of an inverting amplifier, and a feedback filter that shifts the phase by 180° at the oscillation frequency.[6] 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 $V_{\rm in}$ and produces the corresponding output currents i_1 and i_2 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



(a) (b)

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

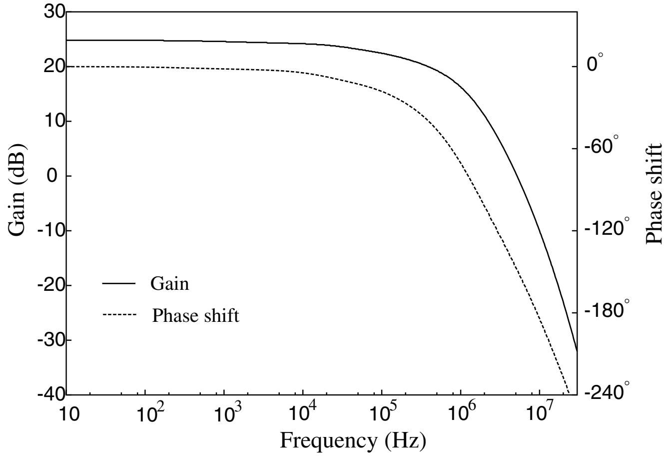


Fig. 9. Simulated frequency response of the heat-conduction amplifier shown in Fig. 8 (SPICE). Log magnitude (or gain) and phase shift of $V_{\mathrm{out}}/V_{\mathrm{in}}$ are plotted as functions of frequency. The gain is 17 dB at 60° phase shift and −9.6 dB at 180° phase shift.

corresponding drain currents. The differential amplifier then produces a phase-shifted output voltage V_{out}.

We designed a heat-conduction amplifier using a parameter set for 0.35-μm CMOS devices and simulated its frequency response. Figure 9 shows the SPICE result (the Bode plot for $V_{\mathrm{out}}/V_{\mathrm{in}}$). The phase shift in the amplifier was larger than that in the thermal filter alone. This is so because an additional phase shift was 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° phase shift 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, so the triple-phase oscillator was able to oscillate. We simulated the operation of the oscillator. The waveforms of oscillation are shown in Fig. 11. The solid line shows the output voltage (V_{out} in Fig. 8(a)) of an amplifier, and the dashed line shows the difference between the channel temperatures of thermo-sensor MOSFETs in the amplifier. The oscillation frequency was 1.25 MHz, and it is lower than expected from the phase-shifting characteristic (Fig. 7) of the thermal

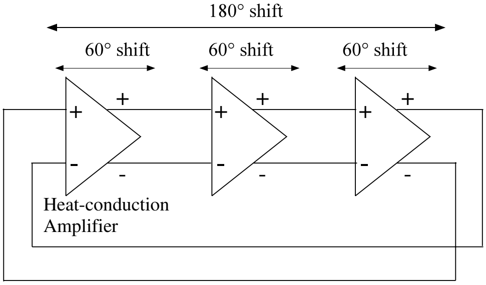


Fig. 10. Triple-phase oscillator consisting of three heat-conducting amplifiers connected into a loop.

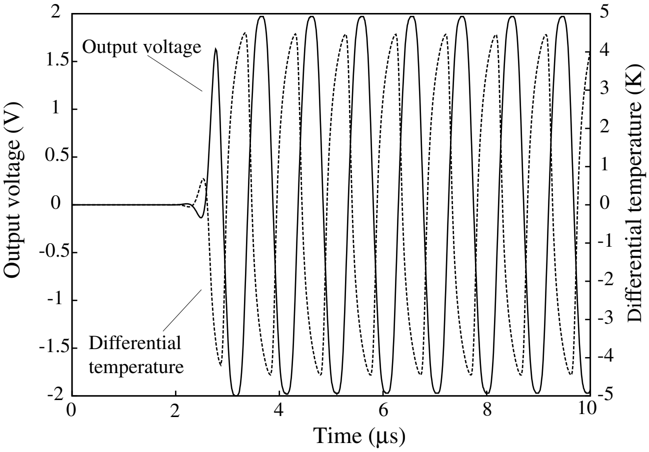


Fig. 11. Simulated oscillation waveforms of simulation results for differential output voltage and differential temperature of an amplifier in the oscillator (SPICE).

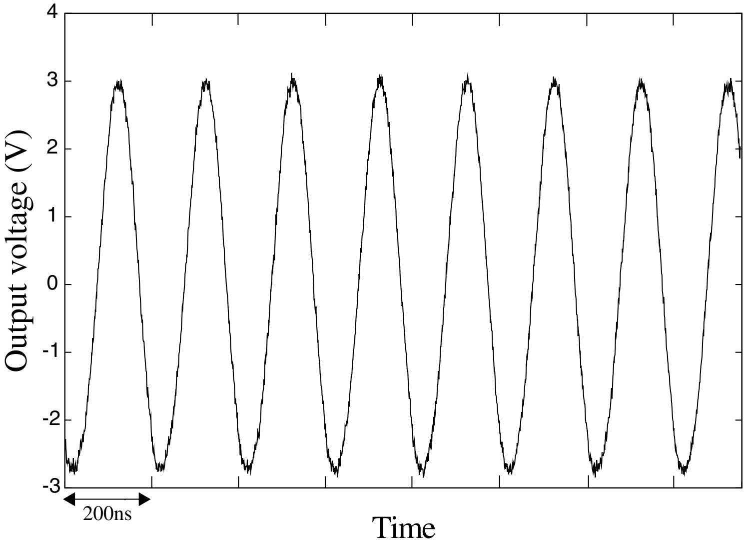


Fig. 12. Measured waveforms of phase-shift oscillation in fabricated oscillator (experimental result).

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.

To confirm the operation of the oscillator experimentally, we fabricated thermal filters using a 0.35-μm CMOS process and constructed a heat-conduction amplifier by combining the fabricated thermal filter with a discrete CMOS amplifier. We then implemented a triple-phase oscillator with three heat-conduction amplifiers. Figure 12 shows the measured waveform for the output of one heat-conduction amplifier. The oscillation frequency was 6.1 MHz and roughly equal to the 60° shift frequency (see Fig. 7) of the thermal filter.

5. Summary

We proposed a CMOS phase-shift oscillator that used a phase shift in the conduction of heat. The oscillator consisted of an inverting amplifier and a feedback thermal filter that could be integrated on a silicon chip.

The proposed circuit would be suitable for fixed low-frequency oscillator (not for variable low-frequency oscillator) where the frequency depends only on (i) size parameters of the thermal filter (i.e., thickness and cross section of S_iO_2 and polySi) and (ii) physical constants of the filter device (thermal conductivity, specific heat and density of S_iO_2 and polySi). Therefore the proposed oscillator with thin (or thick) materials (S_iO_2 and polySi) may exhibit high (or low) frequency oscillation.

Interestingly, the oscillation frequency does not depend on the background (external) temperature. In the circuit, AC components having only 180° phase shift (a few to several tens-MHz) can survive among all the other AC components during the transient heat transfer. Our differential circuit structure is also valuable for canceling influences of the background temperature because common voltages generated by the background temperature on the differential signal lines are subtracted by the differential heat-conducting amplifiers. Consequently, it is unnecessary to control the background temperature for maintaining the oscillation frequency.

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