

High-resistance resistors consisting of subthreshold-operated CMOS circuits ----LSI implementation of 1-1000 mega ohm resistors----

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Abstract

We propose a CMOS circuit that can be used as an equivalent of resistors. This circuit uses a differential pair consisting of diode-connected MOSFETs and operates as a high-resistance resistor when driven in the subthreshold region. Its resistance can be controlled in a range of 1-1000 M Ω by adjusting the driving current for the circuit. The results of the fabrication and measurement of the circuit are described.

Keywords: integrated circuit, resistor, high resistance, differential circuit, subthreshold

1. Introduction

In CMOS integrated circuits, resistors are usually made using doped polysilicon layers. Polysilicon resistors, however, need a very large area if large values of resistance are required. For example, for a 100 mega-ohm resistor, we have to tolerate a large area of 0.2 millimeters square even if we use a 1-k Ω /square high-resistance poly layer and a 0.13- μ m process technology. Large resistances are therefore difficult to implement in integrated circuits.

To solve this problem, we propose a concise circuit that operates as a high-resistance resistor. This circuit consists of a subthreshold-operated CMOS differential pair and can be used as an equivalent of high-resistance resistors. The following provides the details on this resistor circuit.

2. CMOS circuit equivalent to resistors

Figure 1 illustrates the principle of our resistor circuit. The circuit consists of diode-connected differential pair (M1, M2) driven by tail current I_0 . The load currents (denoted by $I_0/2$) are fixed to half of the tail current. In this circuit, given a voltage ΔV between terminals 1 and 2, a current ΔI flows into terminal 1 and an equal current ΔI flows out of terminal 2. This

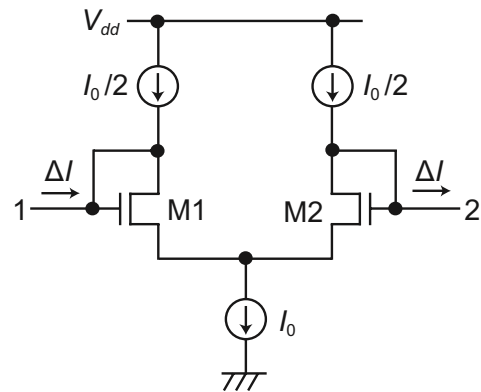


Fig. 1 Outline of resistor circuit equivalent of a resistor with terminals 1 and 2.

current ΔI is proportional to ΔV if the differential pair is operated in its linear region. The circuit therefore operates as a resistor with terminals 1 and 2. Its resistance is given by $4mkT/(qI_0)$ if the circuit is operated in the subthreshold region, where m is the subthreshold slope factor, k is the Boltzmann constant, q is the elementary charge, and T is temperature. We can easily make a 100-M Ω resistor with a tail current of 1 nA.

3. Circuit design and fabrication

Figure 2 shows the entire configuration of our resistor circuit with a biasing subcircuit. We fabricated the circuit, using a 0.35- μ m 2P-4M CMOS process technology. The aspect ratios $W(\mu\text{m})/L(\mu\text{m})$ of MOSFETs used for device fabrication are given in the figure. The size of the circuit was 105 $\mu\text{m} \times$ 110 μm .

In actual circuits, zero-volt currents ΔI_1 and ΔI_2 (see Fig. 3), or offset currents, flows through the resistor because of imbalances between MOSFETs in the circuit. This offset current consists of two components,

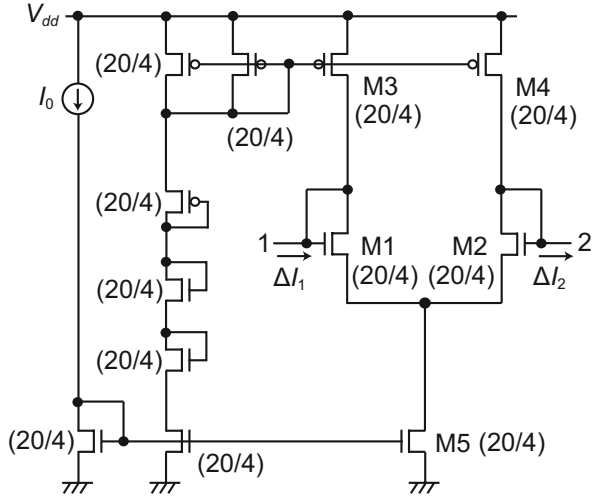


Fig. 2 Resistor circuit with biasing subcircuit. Aspect ratio W/L (μm) used for device fabrication is given for each MOSFET.

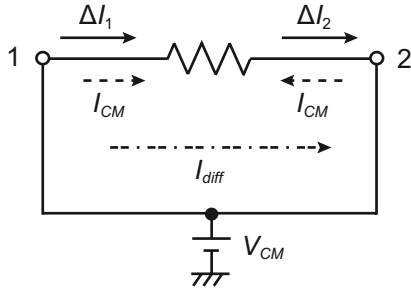


Fig. 3 Offset currents of resistor circuit. Offset currents ΔI_1 and ΔI_2 consist of common-mode offset current I_{CM} and differential offset current I_{diff} .

i.e., (i) common-mode offset current I_{CM} that flows into both terminals of the resistor, and (ii) differential offset current I_{diff} that flows from terminal 1 to terminal 2. That is, $\Delta I_1 = I_{diff} + I_{CM}$ and $\Delta I_2 = I_{diff} - I_{CM}$. The common-mode offset occurs if the currents ratio of M5 to M3-M4 is not 2:1. The differential offset occurs if currents in M1-M3 and M2-M4 are not equal with each other. This has influence on the resistance characteristic as follows.

Figure 4 shows the voltage-current (ΔV - ΔI) curve of the circuit, measured for $I_0 = 1$ nA. The characteristic was almost linear for voltages from -40 to 40 mV. The offset currents influenced the resistance characteristic: that is, (a) ΔV - ΔI curve did not pass the zero point, and (b) current ΔI_1 (solid line) flowing into terminal 1 was

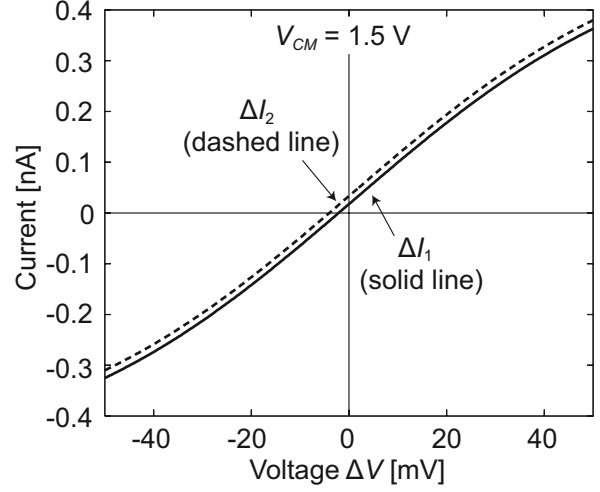


Fig. 4 Voltage-current characteristic of resistor circuit, measured for $I_0 = 1$ nA, $V_{dd} = 3$ V, and V_{CM} (common-mode voltage for terminals 1 and 2) = 1.5 V.

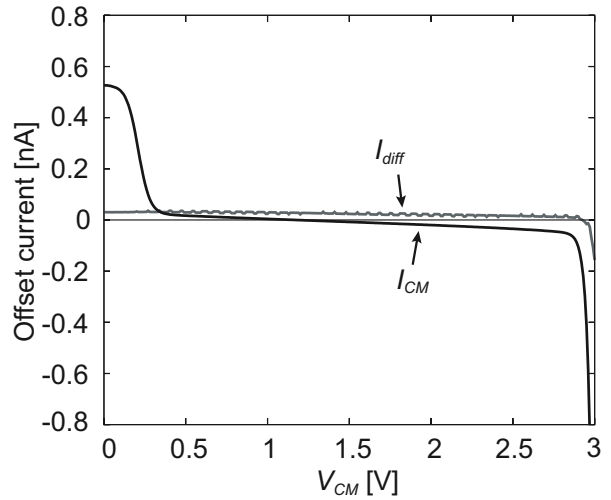


Fig. 5 Offset currents as a function of common-mode voltage V_{CM} for terminals 1 and 2, measured for $I_0 = 1$ nA and $V_{dd} = 3$ V.

not exactly equal to current ΔI_2 (dashed line) flowing out of terminal 2.

Figure 5 shows the common-mode offset current and the differential one as a function of common-mode voltage V_{CM} for terminals 1 and 2, measured for $I_0 = 1$ nA. In this example, for a V_{CM} in a range of 0.4 - 2.8 V, the offset currents are small, so the circuit

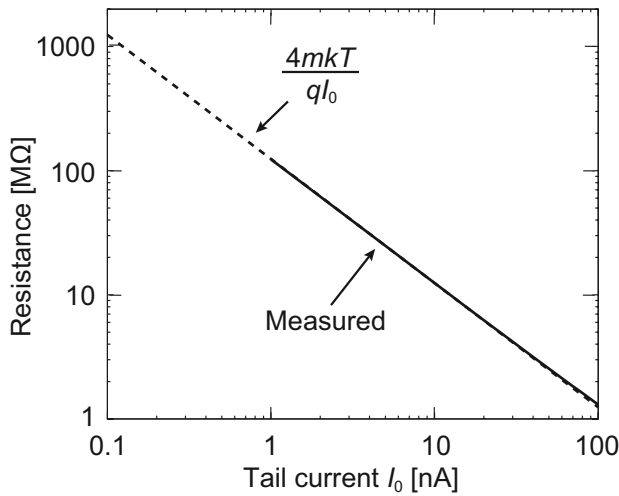


Fig. 6 Resistance of resistor circuit as a function of tail current I_0 . Solid line shows measured data, and dashed line shows theoretical resistance.

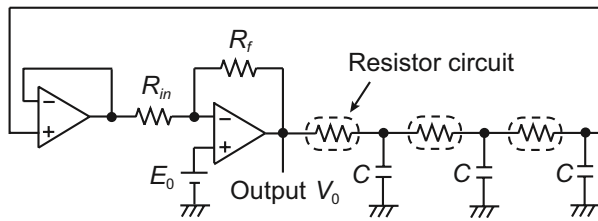


Fig. 7 CR phase-shift oscillator. The elements circled by dashed lines represent resistor circuits.

can be used as a resistor.

Figure 6 shows the resistance as a function of tail current I_0 . The resistance was inversely proportional to I_0 and, for example, 123 MΩ for $I_0 = 1$ nA at room temperature.

4. Application---phase-shift oscillators

As an application, we made a CR phase-shift oscillator, using a low-pass filter consisting of our resistor circuits and capacitors. Figure 7 depicts the configuration, and Figure 8 shows the chip photograph. The oscillation frequency was theoretically given by $f = \sqrt{6} / (2\pi CR)$, where R is resistance and C is capacitance in the low-pass filter. Figure 9 shows measured waveforms of oscillation output. The frequency was 290 Hz for $C = 10$ pF and $I_0 = 1$ nA,

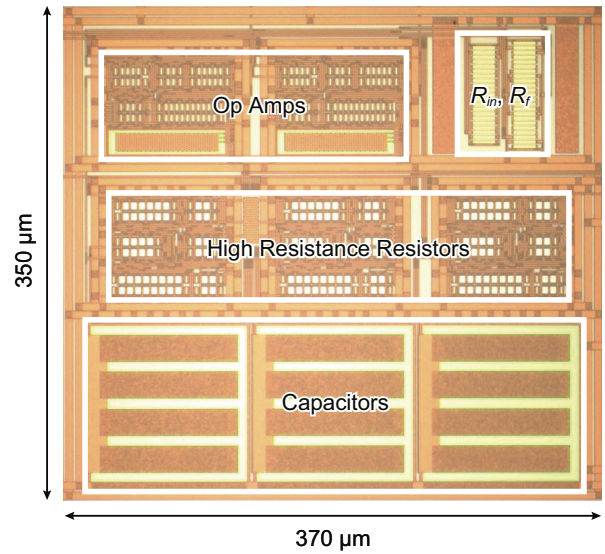
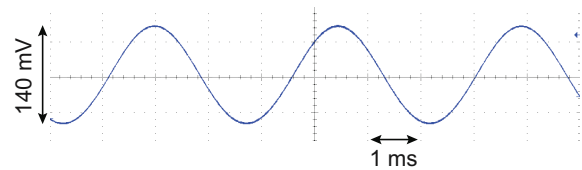
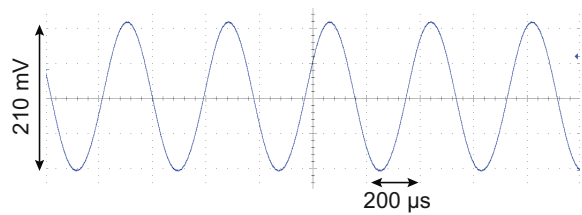


Fig. 8 Chip photograph of phase-shift oscillator. Chip size is $350 \mu\text{m} \times 370 \mu\text{m}$. Parameters used for fabrication were $R_{in} = 5 \text{ k}\Omega$, $R_f = 170 \text{ k}\Omega$, $C = 10 \text{ pF}$, $V_{dd} = 3 \text{ V}$, and $E_0 = 1.5 \text{ V}$.



(a) $I_0 = 1 \text{ nA}$



(b) $I_0 = 10 \text{ nA}$

Fig. 9 Output waveforms of phase-shift oscillator, measured for two values of tail current I_0 for resistor circuit.

and 2.7 kHz for $C = 10$ pF and $I_0 = 10$ nA. Our resistor circuit can provide high resistance easily, so we can build sine-wave oscillators for very low frequency applications.

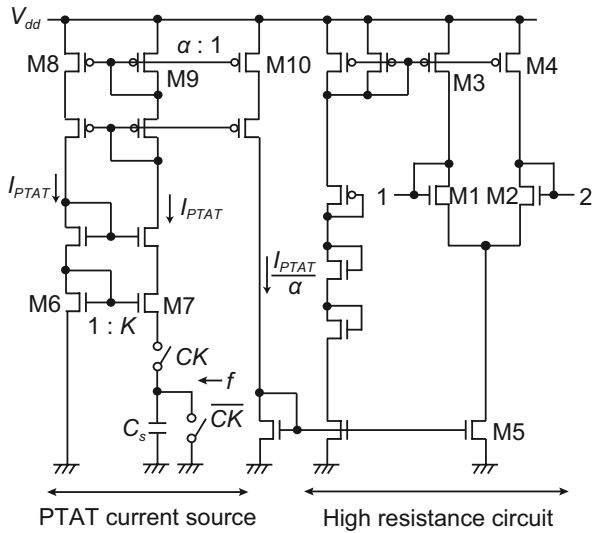


Fig. 10 Resistor circuit with temperature compensation.

5. Temperature compensation

The resistance of our circuit is $4mkT/(qI_0)$ and is proportional to temperature if tail current I_0 is constant. To cancel this temperature dependence, we designed an improved circuit that used a PTAT current (Proportional To Absolute Temperature current) as the tail current.

Figure 10 shows this circuit. A PTAT current source forms a β multiplier self bias circuit consisting of current mirrors (M6-M9 and other four transistors) and a switched-capacitor resistor (C_s and CK , \overline{CK}). The PTAT current I_{PTAT} is given by $mkTC_s f \ln K/q$ if the MOSFETs are operated in the subthreshold region, where f is the switching frequency and K is the aspect ratio of M6 to M7. In this circuit, we set aspect ratio of M9/M10 to $\alpha : 1$, so the tail current of the circuit was I_{PTAT}/α . Therefore, theoretical resistance between terminals 1 and 2 is $4\alpha/(C_s f \ln K)$ and independent of temperature.

We simulated the temperature dependence, using a set of 0.35 μ m-CMOS device parameters. Figure 11 shows the temperature characteristic of the PTAT currents I_{PTAT} with the switching frequency as a parameter. The current changes linearly with temperature. Figure 12 shows the temperature dependence of the resistance. The temperature coefficient (TC) was 260-600 ppm/ $^{\circ}$ C (solid lines) for resistances from 20 to 140 M Ω . In contrast, as shown

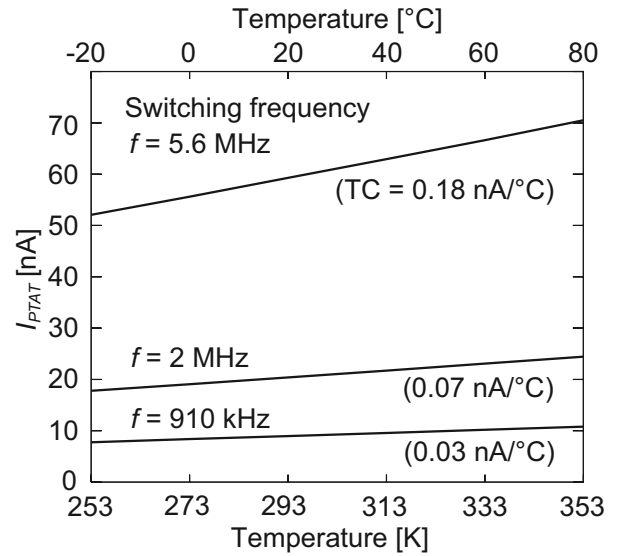


Fig. 11 Temperature characteristic of PTAT current source for three switching frequencies.

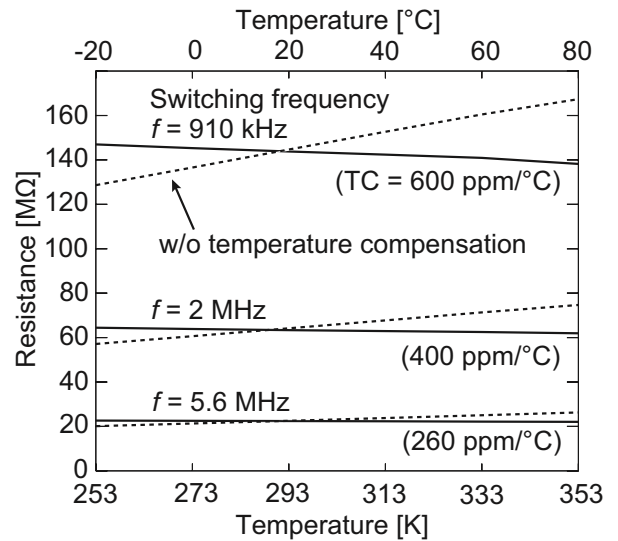


Fig. 12 Temperature characteristic of resistor circuit with compensation. Parameters used for fabrication were $V_{dd} = 3$ V, $\alpha = 10$, $K = 2$, $C_s = 0.55$ pF.

by dashed lines, TC was 2610-2660 ppm/ $^{\circ}$ C without temperature compensation (i.e., tail current is constant). Thus, we were able to obtain high-resistance resistors with a small temperature coefficient.