HIGH-VOLTAGE OPERATIONAL AMPLIFIER BASED ON DUAL FLOATING-GATE TRANSISTORS

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ABSTRACT

A high-voltage operational amplifier (hvopamp) using dual-input floating-gate transistors for its feedback network is presented. The proposed hvopamp stabilizes the output DC voltage in the middle of its high-voltage power supply. Using floating-gate transistors eliminates the need for high-voltage resistor feedback networks. The integral nonlinearity (INL) of the hvopamp with floating gate feedback is 7% in the rail-to-rail output range, which is better than the performance of circuit using parasitic field-oxide MOS transistor as feedback network. The designer does not need to develop a new component, and can implement easily floating-gate transistors in most technologies, which facilitates design and improves the circuit robustness.

I. INTRODUCTION

In the last few years, high-voltage integrated circuits have attracted much interest. They target a growing market spurred by a wide range of applications, including display drivers, automotive electronics, small DC motor control, switching regulators and telecommunication circuits. High-voltage amplifiers are used in piezoelectric-based microrobot [1], medical application of electroporation [2], and some electrostatic actuators [3] [4].

Some hvopamp are available in the literature [1] [5] and in commercial products [6]-[8]. All these hvopamp use feedback resistors to provide a dc-stabilized voltage gain. There are some drawbacks of this resistance feedback network. First, the output stage should provide a quiescent current to drive the resistance feedback network, which consumes a lot power. Normally, high resistance is chosen to decrease the quiescent current. Second, these integrated high value high voltage resistances are large, inaccurate and not very stable. To avoid these drawbacks, a hvopamp using field-oxide transistors for the feedback network was developed [9]. It uses some parasitic field-oxide transistors connected to the output terminal, which provide feedback to stabilize the output dc voltage. However, field oxide could be expected to cause drift in the transistor conduction characteristics. On the other hand, the feedback network in [9] is not linear; the feedback current of field-oxide transistors is not proportional to the output voltage, which causes significant integral nonlinearity (INL). Moreover, the designers should develop and model the field-oxide transistor by themselves, because these transistors are not available in both low-voltage and high-voltage technologies.

Floating-gate transistors are widely used in some circuit designs, such as analog memory elements; part of capacitive-based circuits; and adaptive circuit elements [10]. In this paper, floating-gate transistors are used in a new application. We propose a hvopamp using floating-gate transistors in the feedback network to stabilize its output DC voltage, which is implemented by using a 0.8μm CMOS/DMOS high-voltage technology from Dalsa Semiconductor Inc. The structure and operation of the proposed circuit are described in section II, the simulation results and performances are presented in section III.

II. STRUCTURE AND OPERATION

Figure 1 shows a simplified schematic of the proposed hvopamp. This hvopamp is composed of four parts: an input stage, a second stage, a high-voltage output stage and a voltage feedback network.

The input stage, composed of transistors M_1 to M_4, is a linear differential tranconductor using transistors primarily in the triode region [11]. The gates of transistors M_3 and M_4 are connected to the differential input voltage, as a result, triode transistors M_3 and M_4 undergo varying bias conditions to improve the linearity of the input stage.

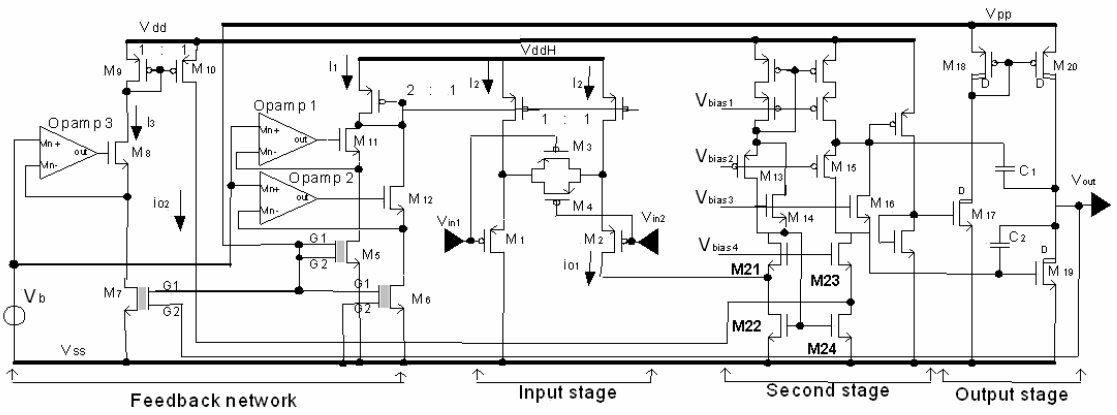

Figure 1: Simplified schematic of the proposed high-voltage amplifier

The power supply (V_{ddH}) of the input stage comes from a charge pump, and is 1.6 to 1.8 times the low-voltage power supply (V_{dd}) used in the second stage and feedback network, which expands the common-mode input voltage range of the differential input stage.

The second stage is a gain stage. The floating current source (M_{13} to M_{16}) provides the quiescent current [12]. The current mirrors, M_{21} to M_{24}, are loaded by the drain current of the input transistor M_2 and the drain current of the M_{10} from the feedback network. The high-voltage output stage is composed of DMOS transistors (M_{17} to M_{20}), where V_{pp} is the high voltage power supply voltage up to 300V in 0.8µm CMOS/DMOS high-voltage technology from Dalsa Semiconductor. The proposed amplifier is compensated using the conventional Miller-capacitances C_1 and C_2.

The voltage feedback network is composed of three linear transconductors: M_5, M_{11} and Opamp1; M_6, M_{12} and Opamp2; M_7, M_8 and Opamp3; where Opamp1 to Opamp3 are simple low voltage amplifier. Dual-input floating-gate MOS (FGMOS) transistors used in these transconductors. The simplified layout of a FGMOS transistor is shown in figure 2a. The floating gate is formed in the gate polysilicon region. Because some gates (control gate) of FGMOS are connected to high voltage supply (V_{pp} or V_{out}), these gates should be implemented by certain layer (metal1 or metal2) that field oxide between control gate layer and floating gate layer can support such high voltage. Figure 2b shows the equivalent model. The voltage of the floating gate V_{FG} is given in equation (1). Where C_T is the sum of all capacitors connected to the floating gate.

$$V_{FG} = \frac{C_{G1}}{C_T} V_{G1} + \frac{C_{G2}}{C_T} V_{G2} \quad (1)$$

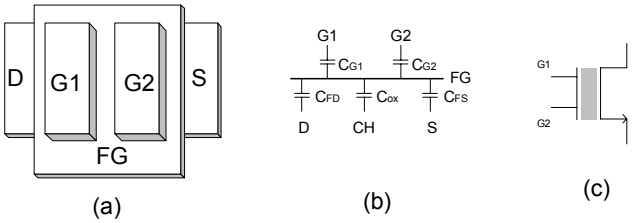

Figure 2: Dual-input FGMOS: (a) Layout, (b) Capacitance model, (c) Symbol

This FGMOS works in triode region. The drain source voltage is set equal to V_b through the use of M_8, M_{11}, M_{12} and three extra opamps. FGMOS M_5 and M_6 generate reference current I_1 to the input stage. Connecting the control gate G1 of FGMOSs to V_{pp} generates an initial bias voltage on the floating gate, which ensures the FGMOSs work in the triode region. Connecting G2 of M5 to V_{pp} ensures that the output voltage converges to the high-voltage rail at a full-scale input. FGMOS M_7 is the feedback transistor from the output signal. It generates current I_3, which is proportional to the output voltage and compares it with the reference I_2 (0.5 I_1).

If we ignore second-order effects, such as velocity saturation and mobility degradation, the current I_1 is shown in equation (2), which is the sum of two FGMOS (M_5 and M_6) currents.

$$I_1 = k_{FG}[(V_{M5FG} - V_t)V_b - \frac{V_b^2}{2}] + k_{FG}[(V_{M6FG} - V_t)V_b - \frac{V_b^2}{2}] \quad (2)$$

where $k_{FG} = \mu C_{ox}(\frac{W}{L})_{FG}$, $V_{M5FG} = \frac{C_{G1} + C_{G2}}{C_T} V_{pp}$

and $V_{M6FG} = \frac{C_{G1}}{C_T} V_{pp}$

The current I_3 is shown in equation (3).

$$I_3 = k_{FG}[(V_{M7FG} - V_t)V_b - \frac{V_b^2}{2}] \quad (3)$$

where $V_{M7FG} = \frac{C_{G1}}{C_T} V_{pp} + \frac{C_{G2}}{C_T} V_{out}$.

Assuming gain product of second and output stages is very high, the input current to the second stage i_{01}, i_{02} should be equal. If there is no input signal ($V_{in} = V_{in1} - V_{in2} = 0$), we have

$$i_{01} = I_2 = 0.5I_1 = i_{02} = I_3 \quad (4)$$

Substituted equation (2) equation and (3) to equation (4), we have

$$V_{out} = \frac{1}{2} V_{pp} \quad (5)$$

The above equation shows the proposed dual-input floating-gate transistor feedback network stabilizes the output DC voltage in the middle of high voltage power supply.

From [11], The transconductance of the input stage G_{min} is given (6)

$$G_{\min} = \frac{4k_1k_3\sqrt{0.5I_1}}{(k_1 + 4k_3)\sqrt{k_1}} \quad (6)$$

The transconductance of the linear tranconductor M_7 G_{MFG} is shown in (7)

$$G_{MFG} = k_{FG} \frac{C_{G1}}{C_T} V_b \quad (7)$$

For the AC response, the current of input stage Δi_{01} should be equal to the feedback current Δi_{02}, which means $\Delta i_{01} = G_{\min} \Delta V_{in} = \Delta i_{02} = G_{MFG} \Delta V_{out}$.

The voltage gain of the proposed amplifier A can be:

$$A = \frac{G_{\min}}{G_{MFG}} = \frac{4k_1k_3\sqrt{I_1}}{(k_1 + 4k_3)\sqrt{k_1}} k_{FG} \frac{C_{G1}}{C_T} V_b \quad (8)$$

III. SIMULATION RESULTS

The proposed circuit was simulated in the following conditions: high voltage power supply V_{pp} was set to 200V, low voltage power supply V_{dd} was set to 5V, and the capacitive load was 100pF. The power supply of the input stage (V_{ddH}) is about 8.4V.

Figure 3 shows the simulated output voltage for a dc differential input voltage. The INL of the amplifier is about 7% in the rail-to-rail output range. Compare 31% (silicon result) INL in reference [9], the proposed amplifier improves the output dc stability. Amplifier nonlinearity is caused by second-order effects, for the transcoductance of the input stage and of the feedback network, such as velocity saturation and mobility degradation.

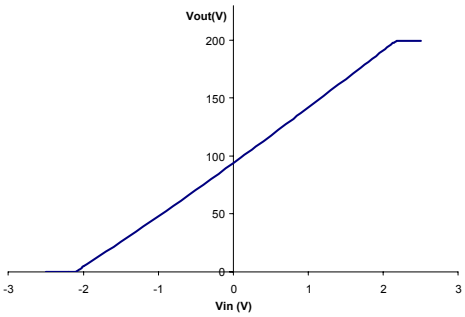

Figure 3: DC sweep of differential input

Table 1: Performances Comparison

	Circuit in [9]	**Proposed circuit**
INL	31% for single output range (measurement)	7% for rail-to-rail output range (simulation)
Fabrication facility	Not available	Available in most of technology
Output range	Single	Rail-to-rail

Figure 3 shows the input offset, which is caused by finite gain of the second and output stage. Also, the transistor mismatch of the input stage could lead to the input offset.

Figure 4 shows the transient response with a 1 kHz 4V peak-to-peak differential input sinusoidal signal.

The output voltage swings from 15 to 185V. Figure 5 shows the simulated small signal frequency response of the proposed hvamp with 100pF load. Table 1 shows the performances comparison of the proposed circuit with the alternate circuit in [9].

A fully differential structure may be developed to eliminate the even order effects of the linear transconductor and improve the integral nonlinearity.

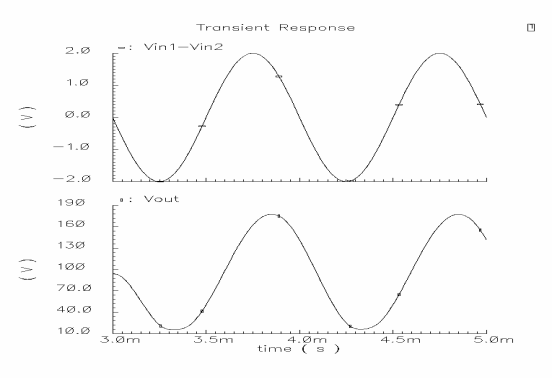

Figure 4: Transient response of a 4V peak to peak differential input sinusoidal signal

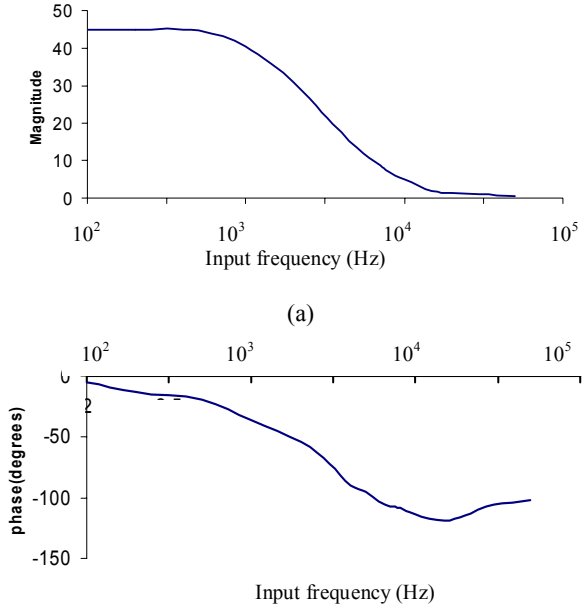

Figure 5: Frequency response of the amplifier (a) Magnitude response (b) Phase response.

IV. CONCLUSION

A new hvopamp using dual-input floating-gate transistors for the feedback network is presented. The proposed hvopamp stabilizes the output DC voltage middle voltage power supply. The integral nonlinearity of the amplifier is 7% in the rail-to-rail output range, which improves performance of circuit using field-oxide transistor. The proposed approach should be more reproducible and easier to control by designers as floating gate transistors characteristics are linearly related to standard devices characterized by all MOS foundries.

V. REFERENCES

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