A Novel Programmable Current Reference with FGMOSFETs

V. Suresh Babu, Varun P. Gopi, Salini Thankachan, and M. R. Baiju

Abstract—High performance analog, digital and power electronic systems need stable, temperature and supply independent reference current. This paper proposes a programmable current reference using floating gate MOSFETs (FGMOSFETs). Multiple reference current can be obtained from the same circuit by programming FGMOSFETs. Subtraction technique is used to compensate the effects of variation in supply voltage and temperature. The proposed circuit has an output current varying from 473.09 nA to 15.71 µA. The circuit performs well over a temperature range of 0°C to 100°C and supply voltage range of 0.5 V to 2.5 V. The circuit has a very low temperature dependency of 1.9 nA/°C and supply voltage dependency of 10.28 nA/V respectively. This circuit avoids the need for re-design and re-fabrication for different values of output current.

Keywords—Floating gate MOSFET (FGMOSFET), bias voltage, subtraction technique, temperature dependency, supply voltage dependency

I. INTRODUCTION

Present day mixed signal circuits become very much attractive as the integrated system gets larger and complex. Highly stable current reference is needed for proper working of analog, digital and power systems. More often band gap reference (BGR) is used to obtain reference current. The positive temperature coefficient of BGR is compensated to obtain stable reference voltage. In standard CMOS process, only lateral parasitic bipolar transistors are available. So these circuits have poor performance. Temperature effect can be reduced by mutual cancellation of mobility and threshold voltage [4], [5]. But the circuits using on-chip resistors and bipolar junction transistors are heavily affected by the process variation. Off-chip resistors increase cost and area [2]. Sub-threshold design and body effects are also used for temperature compensation. Cascaded and feedback structure provides better power supply rejection ratio [6] -[8]. By multiplying a current source which is proportional to mobility and one which is inversely proportional to mobility, temperature dependence can be reduced [9].

FGMOS based circuits are suitable for low voltage applications. The programmability of FGMOS provides post fabrication adjustment of output [10]-[14]. The threshold voltage of FGMOS is programmable by varying one of the control voltage (V_{bias}). A temperature compensated programmable reference voltage is obtained by the charge difference between two Floating Gate transistors [15]. A simple method to obtain supply and temperature compensation is the subtraction technique. By subtracting two current outputs with the same dependencies on the supply voltage and temperature, stable reference current can be obtained [16], [17].

This paper presents a FGMOS based programmable current reference with temperature and supply voltage compensation. The circuit works with a supply voltage as low as 0.5 V. This paper is organized as follows: in section II, the FGMOSFET structure and its principle of operation is explained. Section III describes the proposed programmable current reference circuit. Section IV presents the mathematical analysis of the proposed circuit. In section V, simulation results are presented and conclusion is made in section VI.

II. FLOATING GATE MOSFET (FGMOS)

The FGMOS differs from a conventional MOSFET in that it has one more gate called the floating gate (FG). A Floating Gate MOS Transistor consists of a conventional MOS transistor with its gate surrounded by SiO$_2$. Since the gate surrounded by SiO$_2$ has no DC path to a fixed potential, it is known as Floating Gate. The floating gate is formed by the first poly-silicon layer, while the multiple-input gates are formed by the second poly-silicon layer located above the floating gate. Layout and symbol of FGMOSFET is shown in Fig. 1.

![Fig. 1: Layout and symbol of FGMOS](image)

Fig. 2 shows the equivalent schematic of a typical n-channel, N-input FGMOS. The inputs are only capacitively connected to the Floating Gate (FG), since the FG is completely surrounded by highly resistive material. So, in terms of its DC operating point, the FG is a floating node. The conduction of the FGMOS transistor is different from that of conventional MOS transistor having the same terminal potential, due to
the capacitive coupling between the Floating Gate and control gates. When a voltage is applied to the control gates, capacitive coupling between the control gate and Floating Gate induces an electrical field on the FG. The induced field on the Floating Gate modifies the conductance of underlying channel region [10]-[14], [18].

![Diagram](image)

**Fig. 2: Equivalent circuit of N input FGMOSFET**

The voltage on FG for a two-input FGMOS [10] with \( V_S = V_D = 0 \) V is given by

\[
V_{FG} = \frac{C_1}{C_T} V_1 + \frac{C_2}{C_T} V_2 + \frac{C_{f2d}}{C_T} V_D
\]

(1)

where \( C_T = C_1 + C_2 + C_{f2d} + C_{fab} \) is the total FG capacitance. \( C_1, C_2 \) represents the input capacitances and \( V_1, V_2 \) represents the voltages applied on the input gates. \( C_{f2d} \) and \( C_{fab} \) denote the capacitances from FG to source, drain and bulk respectively.

The drain current of the FGMOS in saturation region is given by

\[
I_D = \frac{\beta}{2} \left[ \left( \frac{C_1}{C_T} V_1 + \frac{C_2}{C_T} V_2 + \frac{C_{f2d}}{C_T} V_D \right) - V_T \right]^2
\]

(2)

where \( \beta = \mu C_{OX} \frac{W}{L} \) is the transconductance parameter. \( C_{OX} \) is the gate-oxide capacitance per unit area, \( \mu \) is the mobility, \( \frac{W}{L} \) is the width to length ratio of MOSFET and \( V_T \) is the threshold voltage.

III. THE PROPOSED PROGRAMMABLE CURRENT REFERENCE CIRCUIT

The proposed current reference is a voltage controlled current source, where the output current \( I_{out} \) varies according to the bias voltage \( V_{bias} \). The circuit diagram of the proposed FGMOS based programmable current source is shown in Fig. 3. The circuit is made programmable by FGMOS \( F_1 \) and \( F_2 \). Programming the charge on the FG transistors provides the flexibility of a programmable reference with the advantage of a single design providing multiple reference output [15]. The current reference consists of two circuits having same dependency on supply and temperature, and a subtractor. \( F_1 \) and \( M_7 \) forms the current mirror in stage I. \( M_3 \) provides suitable bias to \( F_1, M_1, M_2, M_4 \) and \( M_5 \) provide a variable bias to \( M_3 \).

In stage II, \( F_2 \) and \( M_{14} \) forms the current mirror and \( M_{10} \) provide suitable bias to \( F_2, M_8, M_9, M_{11} \) and \( M_{12} \) provide a variable bias to \( M_{10} \). \( M_{15} \) scales the output current from stage I and \( M_{16} \) scales the output current from stage II. The output current of \( M_{16} \) is subtracted from the output current of \( M_{15} \) to obtain the supply and temperature compensated reference current.

IV. MATHEMATICAL ANALYSIS

Applying Kirchoff's voltage law in the output loop of stage I in Fig. 3

\[
V_{SD3} + V_{DSF1} - V_{DS7} - V_{GS6} = 0
\]

(3)

\[
V_{SG3} - V_{TP} + V_{GSF1} - V_{TN} - (V_{GS7} - V_{TN}) - V_{GS6} = 0
\]

(4)

In saturation region the drain current [19] is given by

\[
I_D = \frac{\beta}{2} (V_{GS} - V_T)^2
\]

(5)

Substituting (2) and (5) in (4) results

\[
\sqrt{\frac{2I_1}{\beta_P} + \left( \frac{C_2}{C_T} \right) V_{bias} + \left( \frac{C_1}{C_T} - 1 \right) \left( \sqrt{\frac{2I_1}{\beta_N} + V_{TN}} \right)} = \left( \sqrt{\frac{2I_1}{\beta_N} + V_{TN}} \right)
\]

(6)

where \( I_1 \) is the output current of stage I. On rearranging (6) becomes

\[
I_1 = \frac{1}{2} \left( \left( \frac{C_1}{C_T} - 2 \right) V_{TN} + \frac{C_2}{C_T} V_{bias} \right)^2
\]

(7)

The transconductance parameter \( \beta \) is directly proportional to mobility \( \mu \), the temperature dependent terms in (7) are threshold voltage \( (V_{TN}) \) and transconductance parameter \( \beta \) [3], [4].

The relationship between threshold voltage and temperature is given by (8)

\[
V_T(T) = V_T(T_0) + \alpha_{VT} (T - T_0)
\]

(8)

where \( \alpha_{VT} = \frac{\partial V_T}{\partial T} \) is a negative constant
The relationship between mobility and temperature is given by (9)

$$\mu(T) = \mu(T_0) \left( \frac{T}{T_0} \right)^{\alpha_{\mu}}$$

(9)

where \(\alpha_{\mu}\) is a negative constant [3], [4].

Applying subtraction technique to voltage controlled current source circuit, it is possible to remove temperature and supply voltage effects in the reference current [16], [17]. The reference current is obtained by taking the difference of the output currents from the two stages with scaling factors N, M and can be expressed as in (10)

$$I_{REF} = NI_1 - MI_2$$

(10)

where \(I_2\) is the output current of stage II, which is equal to \(I_1\). Using (7) \(I_{REF}\) can be expressed as in (11)

$$I_{REF} = \frac{(N - M)}{2} \left( \left( \frac{C_1}{C} \right) - 2 \right) V_{TN} + \left( \frac{C_2}{C} V_{bias} \right)^{2}$$

(11)

From (11) it is observed that the reference current does not depend on supply voltage.

V. SIMULATION RESULTS

The simulation of the proposed programmable current reference is carried out using TSPICE provided by TANNER EDA with BSIM model file. Fig. 4 shows the variation of reference current with supply voltage and bias voltage. The supply voltage varies from 0 V to 2.5 V. The reference current varies from 473.09 nA to 15.71 \(\mu\)A as bias voltage varies from 0.6 V to 0.9 V. Fig. 4 shows that the output current is almost independent of supply voltage in the range of 0.5 V to 2.5 V.

Fig. 5 (a) and Fig. 5 (b) show the variation of reference current with supply voltage and temperature for \(V_{bias}=0.9\) V. For \(V_{bias}=0.9\) V the circuit has a supply dependency of 0.175 nA/V and a temperature dependency of 1.9 nA/°C is obtained.

Fig. 6 (a) and Fig. 6 (b) shows the variation of reference current with supply voltage and temperature for \(V_{bias}=0.6\) V.

Fig. 4: Variation of reference current with supply voltage for different values of bias voltage

Fig. 5: Variation of reference current with (a) supply voltage (b) temperature for \(V_{bias}=0.9V\)

Fig. 6: Variation of reference current with (a) supply voltage (b) temperature for \(V_{bias}=0.6V\)
For $V_{bias} = 0.6\text{V}$ the supply voltage dependency is $10.28\text{nA/V}$ and temperature dependency is $8.36\text{nA/}°\text{C}$. The variation of output current with bias voltage is shown in Fig. 7. It closely matches with the analytical model given by (11). As the bias voltage is changed from $0.6\text{ V}$ to $0.9\text{ V}$ the reference current varies from $473.09\text{ nA}$ to $15.71\text{ µA}$.

![Graph showing variation of reference current with bias voltage](image)

**Fig. 7:** Variation of reference current with bias voltage

VI. CONCLUSION

A programmable current reference using FGMOS with temperature and supply voltage compensation is presented. Subtraction technique is used to compensate the dependency of current reference on supply voltage and temperature. The reference current can be varied from $473.09\text{ nA}$ to $15.71\text{ µA}$. Programmability avoids the need for re-design and re-fabrication for different values of output current. It also facilitates post-fabrication adjustments for tuning and error correction. The circuit can operate with a supply voltage as low as $0.5\text{ V}$, with no passive components. The circuit performs well over the temperature range of $0°\text{C}$ to $100°\text{C}$ and supply voltage range of $0.5\text{ V}$ to $2.5\text{ V}$. The circuit has a temperature dependency of as low as $1.9\text{ nA/}°\text{C}$ and a supply voltage dependency as low as $10.28\text{ nA/V}$, which are better than that for reported circuits.

**REFERENCES**


