Programmable Temperature Insensitive Voltage and Current Reference using Floating Gate MOSFETs

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***Abstract*—A temperature insensitive programmable voltage and current reference circuit is proposed. The same circuit provide voltage and current references which can be varied over a wide range and are almost independent of variations in supply voltage and temperature. The key component used is floating gate transistors which make the circuit programmable. The current and voltage references can be varied by varying the bias voltage applied to one of the control gates of floating gate MOSFET. The temperature coefficient for current is obtained as 43ppm/^{0}C, and for voltage as 47ppm/^{0}C over the range of temperature 0 to 100^{0}C. The supply voltage dependency for voltage and current references are 10.15mV/V and 4.2 μA/V respectively over the range of supply voltage 1 to 4 V. The circuit is simulated using Tanner EDA tool with BSIMv3 model.**

***Index Terms*—Voltage and Current reference, temperature insensitivity, β multiplier, floating gate MOSFETS.**

I. Introduction

With the development of CMOS technologies low power and low voltage circuits are used in portable electronics equipments, which reduces the power consumption and increases the circuit stability. Many of these circuits need a stable source (voltage or current) over temperature and supply variations. Voltage and current references generate reference voltage and current which are independent of temperature, supply voltage and process variations. They are key components in analog and mixed signal circuits such as A/D and D/A converters, PLLs, on chip oscillators, flash memories etc.

Different schemes are used to implement voltage references. In bandgap reference [1], [2], [3] a temperature independent voltage reference is generated by adding two quantities having opposite temperature coefficients with proper weighting factors. In [4], [5] the reference voltage is obtained by the gate source voltage reference between two MOS transistors. Temperature insensitive voltage is generated by mutually compensating the temperature dependencies of the threshold voltage of a PMOS and an NMOS transistor. The output reference voltage is obtained by subtracting $|V_{thp}|$ from scaled V_{thn}. Threshold voltage based reference circuits [6], [7], [8] utilizes the negative temperature coefficient of the threshold voltage of the MOSFET. Threshold voltage is added with a thermal voltage or a voltage with positive temperature coefficient which is generated by bias circuits.

In this paper we propose a temperature insensitive voltage and current reference in a single circuit. The temperature independent output is generated by the beta multiplier self biasing circuit. Since the circuit uses FGMOS as the key component, it is suitable for low voltage applications. Programmability is achieved by varying the external bias voltage of the FGMOS.

This paper has the structure as follows. Section II gives an introduction to floating gate MOSFETS and section III describes the basic principle of voltage and current reference circuit using MOSFET. The proposed circuit and its mathematical analysis are given in section IV. Section V reports the simulation results and section VI gives the concluding comments.

II. Floating gate MOSFETS

Now a days low voltage and low power circuits have greater demand. FGMOS circuits are suitable for these applications. FGMOS is similar to an ordinary MOSFET, exept that its gate is floating because gate is electrically isolated and realized using the double polysilicon process. First polysilicon layer forms the floating gate and the second layer forms the multiple input gates. Several control gates are possible over the floating gate. Floating gate is capacitively coupled to the multiple input gates and controls the channel current. As the effective threshold voltage can be altered, it is suitable for low voltage applications.

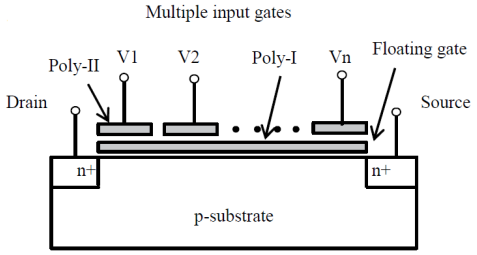


Fig. 1: Structure of Multiple input FGMOS

The structure of multiple input FGMOS is shown in figure 1 . V_1, V_2, ...V_n are the n input voltages. In a two-input FGMOS, first gate (G_1) is used as signal (V_1) input gate and

the second gate is used as bias (V_2) input gate. This external bias voltage can be used to modulate the channel current[9], [10]. Figure 2 shows the symbol and equivalent circuit of FGMOS.

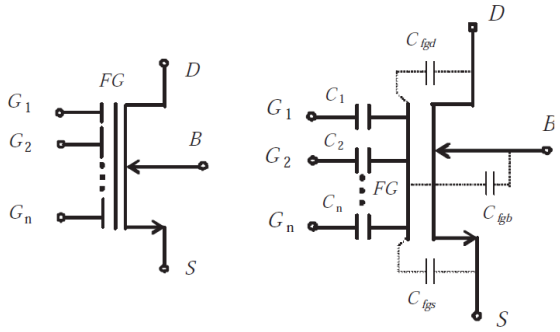


Fig. 2: Symbol and Equivalent circuit of Multiple input FGMOS

The drain current (I_D) of the FGMOS when operating in ohmic region is given by:

$$I_D = \beta \left[\left(\frac{C_1}{C_{total}} V_1 + \frac{C_2}{C_{total}} V_2 + \frac{C_{fgd}}{C_{total}} V_{DS} \right) V_T - \frac{V_{DS}}{2} \right] V_{DS} \quad (1)$$

where β is the transconductance parameter, C_1 and C_2 are the internal capacitances in the equivalent circuit. $C_{total} = C_1 + C_2 + C_{fgb}$ is the total floating gate capacitance. V_T is the threshold voltage.
The drain current (I_D) of the FGMOS operating in saturation is obtained by modifying (1) as

$$I_D = \frac{\beta}{2} \left[\left(\frac{C_1}{C_{total}} V_1 + \frac{C_2}{C_{total}} V_2 + \frac{C_{fgd}}{C_{total}} V_{DS} \right) - V_T \right]^2 \quad (2)$$

III. Voltage and Current Reference using MOSFETs

A temperature insensitive voltage and current reference circuit using CMOS is presented in [11] and the circuit is shown in figure 3. The reference generator circuit was a hybrid of the PTAT current reference circuit. The current generated with this circuit is given by

$$I_{ref} = \frac{U_T}{R} ln \frac{S_2 S_4}{S_1 S_3} \quad (3)$$

U_T is the thermal voltage and S is the aspect ratio of the transistors. Temperature insensitivity is attained with the compensation of the thermal voltage change with the additional active load transistor(M_{NC}).

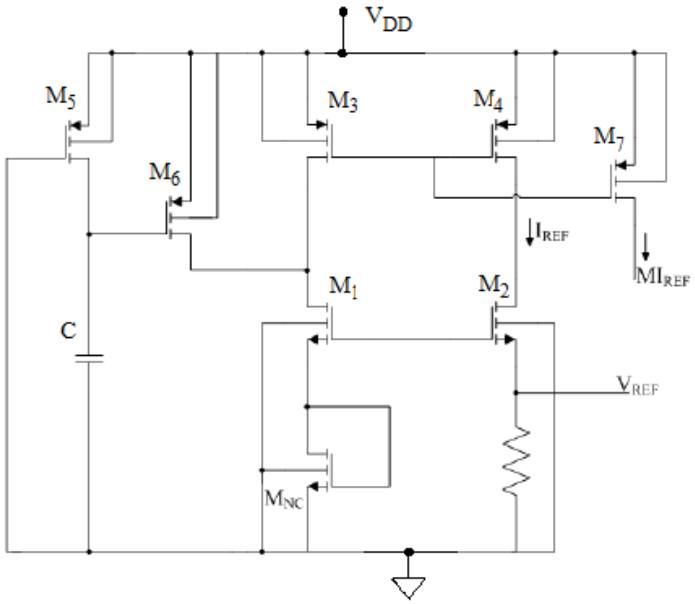


Fig. 3: Voltage and Current Reference using MOSFET

IV. Proposed Circuit

The proposed temperature insensitive voltage and current reference circuit is shown in figure 4. Since the circuit uses FGMOS as the key element instead of MOSFET, it is suitable for low voltage applications, and this circuit is also programmable (it provides a range of output voltage and current from a single circuit) . The circuit uses the β multiplier self biasing scheme [12], [13] to attain the temperature stability. In figure 4 the transistors M_5, M_6 and C constitutes the startup circuit. When starting up M_5 turns on and charges C untill M_6 turns on, then M_5 injects current to the branch of bias circuit and it starts to work accurately. M_1, M_2, M_3, and M_4 are floating gate MOSFETS. The current flowing through the resistor R_2 and the voltage across the resistor R_3 are the reference current and voltage respectively.

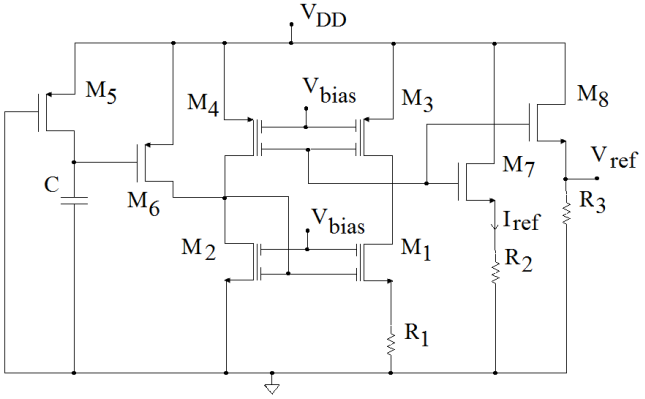


Fig. 4: The proposed circuit of temperature insensitive voltage and current reference using FGMOS

A. β multiplier self biasing

A β multiplier circuit is shown in figure 5. When temperature increases, the voltage drop across R also increases, because of the positive temperature coefficient of the resistor and compensates the decrease of the gate source voltage of M_2 due to the negative temperature coefficient of its threshold voltage. A constant reference voltage can thus be maintained.

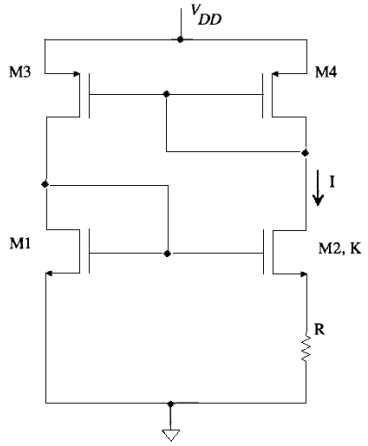


Fig. 5: β multiplier circuit

The width of M_2 is made K times larger than the width of M_1, so that

$$\beta_2 = K\beta_1$$

assuming $L_1 = L_2$ and $W_2 = K.W_1$

$$V_{GS1} = V_{GS2} + IR \tag{4}$$

$$V_{GS1} = \sqrt{\frac{2I}{\beta_1}} + V_T \tag{5}$$

$$V_{GS2} = \sqrt{\frac{2I}{K.\beta_1}} + V_T \tag{6}$$

$$IR = \sqrt{\frac{2I}{\beta_1}} + V_T - \sqrt{\frac{2I}{K.\beta_1}} - V_T \tag{7}$$

and

$$I = \frac{2}{R^2.\beta_1}.\left(1 - \sqrt{\frac{1}{K}}\right)^2 \tag{8}$$

The temperature coefficient of the current reference is given by

$$TC_I = \frac{1}{I}.\frac{\partial I}{\partial T} = -2.\frac{1}{R}.\frac{\partial R}{\partial T} - \frac{1}{K_P(T)}\frac{\partial K_P(T)}{\partial T} \tag{9}$$

where

$$K_P = \mu C_{ox}$$

Reference voltage

$$V_{ref} = V_{GS1} = \sqrt{\frac{2I}{K.\beta_1}} + \frac{2}{R\beta_1}\left(1 - \sqrt{\frac{1}{K}}\right)^2 + V_T \tag{10}$$

Variation of reference voltage with temperature is given by

$$\frac{dV_{ref}}{dT} = \frac{2}{R\beta_1}\left(1 - \sqrt{\frac{1}{K}}\right)\left[R.\frac{\partial K_P}{\partial T} + K_P\frac{\partial R}{\partial T}\right] \tag{11}$$

B. Circuit Analysis

In the proposed circuit shown in figure 4 two input floating gate MOSFETs are used, where V_1 is equal to V_{bias} and V_2 equal to V_{GS} of the FGMOS.
In the case of transistor M_2, $V_{DS2} = V_{GS2}$. The width of M_1 is made K times larger than the width of M_2

$$\beta_1 = K\beta_2$$

assuming $L_1 = L_2$ and $W_1 = K.W_2$
Considering the loop $M_2 - M_1 - R_1$.

$$V_{GS2} = V_{GS1} + IR_1 \tag{12}$$

From (1) we get

$$V_{GS} = \frac{C_{total}}{C_2}\left[\sqrt{\frac{2I}{\beta}} + V_T\right] - \frac{C_1}{C_2}V_{bias} - \frac{C_{fgd}}{C_2}V_{DS} \tag{13}$$

For transistor M_2, $V_{GS2} = V_{DS2}$

$$V_{GS2} = \frac{C_{total}}{C_{22}}\left[\sqrt{\frac{2I}{\beta_2}} + V_T\right] - \frac{C_{21}}{C_{22}}V_{bias} - \frac{C_{fgd}}{C_{22}}V_{GS2} \tag{14}$$

ie

$$V_{GS2} = \frac{\frac{C_{total}}{C_{22}}\left[\sqrt{\frac{2I}{\beta_2}} + V_T\right] - \frac{C_{21}}{C_{22}}V_{bias}}{1 + \frac{C_{fgd}}{C_{22}}} \tag{15}$$

C_{21} and C_{22} are the internal capacitances associated with the FGMOS transistors and value of these capacitances are in the range of femto Farad. Assume $\frac{C_{fgd}}{C_{22}} << 1$. Therefore $1 + \frac{C_{fgd}}{C_{22}} \approx 1$.

So (15) reduces to (16)

$$V_{GS2} = \frac{C_{total}}{C_{22}}\left[\sqrt{\frac{2I}{\beta_2}} + V_T\right] - \frac{C_{21}}{C_{22}}V_{bias} \tag{16}$$

Also

$$V_{GS1} = \frac{C_{total}}{C_{12}}\left[\sqrt{\frac{2I}{K\beta_2}} + V_T\right] - \frac{C_{11}}{C_{12}}V_{bias} - \frac{C_{fgd}}{C_{12}}V_{DS1} \tag{17}$$

Substituting eqns (16) and (17) in (12), squaring and rearranging we get current reference (I_{ref}) as in (18)

$$I_{ref} = \frac{\left[\frac{C_{total}}{C_{22}} - \frac{C_{total}}{C_{12}\sqrt{K}}\right]^2 \left(\frac{2}{\beta_2} + V_T^2\right) - V_{bias}^2 \left[\frac{C_{21}}{C_{22}} - \frac{C_{11}}{C_{12}}\right]^2 + \frac{C_{fgc}^2}{C_{12}^2}}{R_1^2} \tag{18}$$

and reference voltage

$$V_{ref} = I_{ref} R_1 \tag{19}$$

Let

$$\left[\frac{C_{total}}{C_{22}} - \frac{C_{total}}{C_{12}\sqrt{K}}\right]^2 = \alpha$$

The temperature coefficient of reference current TC(I_{ref})

$$TC(I_{ref}) = \frac{dI_{ref}}{dT} = \frac{d}{dT}\left[\frac{\alpha}{R_1^2}\left(\frac{2}{\beta_1} + V_T^2\right)\right] \tag{20}$$

In this equation mobility, threshold voltage and resistance are the temperature dependent parameters.

$$\frac{dI_{ref}}{dT} = \frac{2\alpha}{R_1^2}\left(K_{V_T} - K_\mu\right) - \left(\frac{2}{\beta_1} + V_T^2\right)\alpha K_R \tag{21}$$

Assume K_μ , K_{V_T} and K_R are the temperature coefficients of mobility, threshold voltage and resistance respectively.
The value of R_1 for temperature independent current is obtained by equating $\frac{dI_{ref}}{dT}$ to zero as given by (21).

Then

$$R_1 = \sqrt{\frac{2\left(K_{V_T} - K_\mu\right)}{K_R\left(\frac{2}{\beta_1} + V_T^2\right)}} \tag{22}$$

V. Simulation Results and Discusion

The proposed circuit is simulated using the Tspice of Tanner EDA tool with BsimV3 model. With the help of the circuit analysis R_1 is designed and obtained as 100Ω, and the value of the resistors R_2, R_3 and capacitor C are 1KΩ, 10KΩ and 10pF respectively.

A. Programmability of the circuit

The new voltage and current reference circuit generate a range of output voltages and current almost independent of temperature and supply voltage. V_1 is one of the control input voltage of the FGMOS and is used as the bias voltage, and by varying V_{bias} we get a range of outputs. Programmability of the circuit for the range of V_{bias} of 0.5V to 1.5V is shown in figure 6. Figures 6a and 6b show the variation of output current and voltage respectively with the bias voltage. The circuit generates voltage and current outputs in the range of 0 to 450mV and 0 to 180μA for the range of V_{bias} voltages 0.5V to 1.5V.

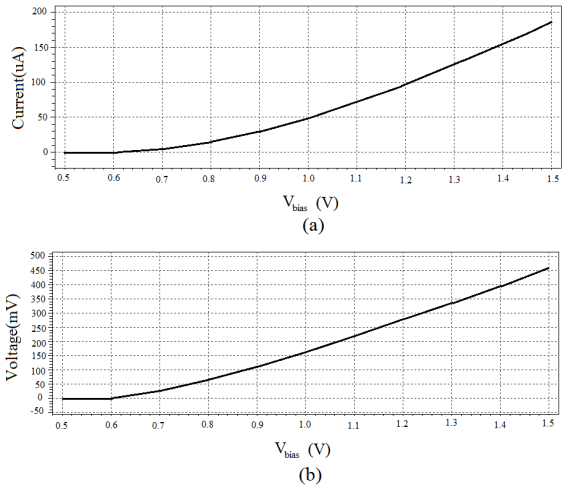


Fig. 6: (a) Variation of output current with bias voltage
(b) Variation of output voltage with bias voltage

B. Supply voltage and Temperature independency

Figure 7a shows the variation of output current with supply voltage for different bias voltages and figure 7b shows the output voltage variation with supply voltage for different bias voltages. It shows that the outputs are almost independent of supply voltage over the range of 1-4 V. The output shows a maximum variation of 4.2$\mu A/V$ and 10.15mV/V for output current and voltage respectively.

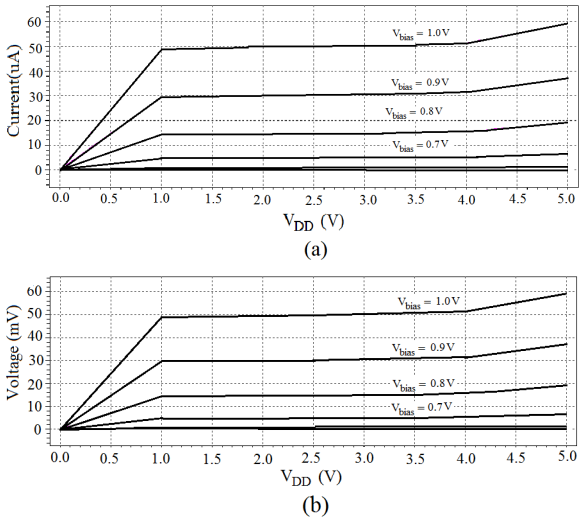
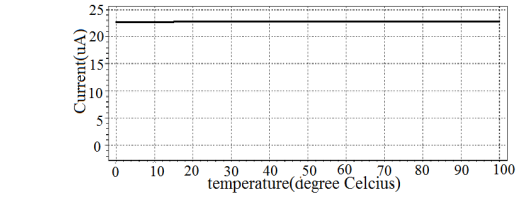


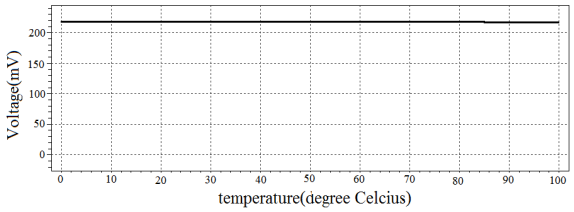
Fig. 7: (a) Variation of current with supply voltage for different bias voltages
(b) Variation of voltage with supply voltage for different bias voltages

The β multiplier self biasing scheme makes the circuit almost temperature and supply independent. The best temperature independent current reference output is obtained for V_{bias}=0.86V and the temperature coefficient obtained over the range of temperature 0 to 100^0C is 43ppm/^{0}C, and at a V_{bias}=1.1V best temperature insensitive voltage is obtained

with a temperature coefficient of 47ppm/^{0}C. Temperature independent values obtained for output voltage and current are 23.9μA and 217.19mV respectively. Temperature insensitive current and voltage references are shown in figures 8a and 8b respectively. Temperature coefficient of current at V_{bias}=0.86V and voltage at V_{bias}=1.1V over the range -45 to 125^{0}C is obtained as 113.45ppm/^{0}C and 29.02ppm/^{0}C. Temperature independency can further be improved by using a subtraction circuit[14].



(a)



(b)

Fig. 8: (a) Variation of output current with temperature (b) Variation of output voltage with temperature

VI. Conclusion

Now a days temperature insensitive and low voltage reference circuits have greater demand. In this paper a voltage and current reference using FGMOS is presented which is temperature insensitive and programmable. Temperature insensitivity is attained with the β multiplier circuit and programmability is attained by varying one of the control input voltages of FGMOS, provides different current and voltage references. The proposed voltage and current reference circuit operates with a supply voltage as 1V. The output current and voltage with an optimum value of temperature coefficient as 43ppm/^{0}C and 47ppm/^{0}C, supply variation of 4.2$\mu A/V$ and 10.15mV/V respectively is obtained. The circuit performance is analyzed and evaluated by simlations. It is found that the analytical and simulation results matches closely.

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