A temperature stable current reference source with programmable output

Axel Thomsen, Martin A. Brooke
Microelectronics Research Center
Georgia Institute of Technology
791 Atlantic Drive
Atlanta, GA 30332-0269
Phone 404-853-9920
FAX 404-894-4700

A current reference source is presented, that achieves stability over temperature with a neural network architecture and floating gate devices. It allows post fabrication adjustment to a user specified output value. Tuning of floating gate devices is also used to accurately cancel temperature gradients at various temperatures. The circuit allows to approximate arbitrary functions over temperature. A first implementation for limited temperature range yielded an accuracy of about 1.5%. Simulation results of an improved version are presented.

Introduction

A reference source is a very important building block in any analog signal processing system. The precision and stability of the reference signal often defines the limit of accuracy in a circuit, for example in A/D or D/A-converters. A reference source should deliver a constant, predictable output over a wide range of temperature and power supply voltage. The design most widely used in integrated circuits is a bandgap-reference [1,2]. The temperature gradients of a pn-junction and a resistor are added in a weighed sum to cancel to zero. The generated voltage is approximately equal to the bandgap voltage of silicon. The weighed sum is generally implemented with an operational amplifier and fixed weights. Current references can be implemented relying on a similar cancellation with a weighed sum [3].

Semiconductor device parameters vary widely between fabrication runs. This causes problems for the design of any reference source in two ways: The absolute value of the reference is not accurately predictable and the temperature coefficients of the devices and subcircuits are not accurately known. Thus the appropriate weights for the cancellation of gradients are not known. The example of a typical CMOS current reference [3] shows 3% variation over a temperature range of 0 to 80°C, a standard deviation of the output value of 2.5% for the same batch and 15% for different batches. This is insufficient for a converter that can achieve an accuracy of 7 bits or higher.

Post-fabrication adjustments are not uncommon for reference sources. Most published implementations use digital adjustments to achieve an accurate gradient cancellation because the temperature parameters cannot be predicted precisely. The application of EEPROMs appears to be a logical step to improve the accuracy and the stability of references by using its high precision adjustment capabilities [4]. But the use of an EEPROM as analog weight in an existing design will not necessarily improve the performance achieved with digital adjustments. The device will add on its temperature-coefficient. Furthermore the assumption underlying this work is the poor predictability of device behavior. Simple gradient cancellation will not necessarily provide temperature stability over a wide range. The condition

$$\frac{k_1}{I_1}\frac{\partial I_1}{\partial T}=\frac{k_2}{I_2}\frac{\partial I_2}{\partial T}$$

holds only for one point, which may lead to deviations over the full temperature range. If the device behavior is difficult to predict, a more sophisticated approach is required.

The Design Idea

Analog EEPROM technology which is available in standard double-polysilicon processes [5] appears to be a good way to achieve accuracy in spite of high parameter variations, because it allows accurate and compact post-fabrication trimming to adapt to given parameters. This flexibility can be utilized in the following applications:

- EEPROMs allow devices to operate in depletion mode, thus being a simple current source with little power supply dependence.
- The absolute value of the reference current can be adjusted with EEPROMs
- The temperature gradient can be compensated accurately with a piece-wise linear function that can be fit to measured data
- The temperature dependence can be adjusted to keep another parameter (f. e. transconductance) constant.

The basic requirement to do cancellation of gradients is the presence of two different temperature dependent functions. A weighed sum of these functions will yield a function, that has zero gradient in one point. Going further away from this point the deviation from this value usually increases. To achieve good stability over a wide temperature range the weighed sum of several functions can be adjusted for zero gradient in several points. To simplify adjustments the functions to be added up should have a shape with a certain region of high gradient and otherwise be as flat as possible, preferably constant or zero in a segment for a simplified adjustment procedure. A weight circuit with low temperature coefficient is required to adjust absolute value and weights of the compensation functions for accurate gradient cancellation. Its temperature dependence must not dominate the temperature dependence of the non-linear signal. It needs to be suitable for signals of one sign and weights of either sign that can be stored on a floating gate.

Implementation

Four building blocks are required to implement the circuit idea outlined above: two current sources, one with low temperature coefficient, one with high temperature coefficient, clipping circuits and adjustable weights.

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The ltc-current was achieved by programming an EEPROM into depletion to a bias region where the temperature coefficients of the threshold voltage and the transconductance parameter cancel approximately (fig. 1). Since parameters vary, this operating point may vary, too. Accurate adjustment and gradient cancellation is not required, the temperature coefficient should be about an order of magnitude less than the htc. Simulations show that 0.1%/°C variation is a reasonable value (fig. 2). Capacitive coupling into the floating gate from the substrate has to be avoided for good power supply rejection.
A htc-current was achieved by the unbalanced current mirror circuit shown in fig. 1. The p-type current mirror has a input/output width-ratio of 8. The additional transistor in the input branch of the n-type current mirror causes a strong temperature dependence. A temperature dependent current signal is generated by taking advantage of the negative temperature coefficient of the threshold voltage to lower the gate-source voltage and the decreased transconductance parameter to reduce the output current. The measured output current shows a temperature variation of about 1%/°C (fig. 3).
The clipping circuit is implemented based on unidirectional current mirrors and current sources. Using a current source with a high temperature coefficient (htc), that essentially provides a temperature-signal, a current source with low temperature coefficient (ltc) and a current mirror based clipping circuit (fig. 1), the required functions can be generated. They can be described as

$$I_{out}^{n} = f(I_{htc} - n * I_{ltc})$$

where

$$f(I) = \begin{cases} 0 & \text{for } I < 0 \\ I & \text{for } I_{ltc} > I > 0. \\ I_{ltc} & \text{for } I > I_{ltc} \end{cases}$$

The circuit operates temperature independent.
The main design goal for the weight circuit is adjustability with a floating gate current source and limited temperature dependence. The weight circuit used in the more extensive simulations consists of an input stage of two resistor-connected FETs for both the clipped current signal and the ltc current as a reference. The voltage signal is connected to two differential pairs, one of which is biased with a floating gate device (fig. 4). Zero output current is achieved for high temperatures with I_{ltc} being larger than I_{chop}. A region of gain is present where I_{chop} changes. The remainder of the transfer function is dominated by the ltc and thus smaller than in the gain region (see fig. 5). By adjusting the biasing of one differential pair the weight can be adjusted to within a certain range. Linearity is of no concern for this multiplier. The circuit used in the first implementation is an adjustable current mirror based on two differential transconductance amplifiers [6]. Its adjustment is more difficult.
An EEPROM device in depletion mode is used as the adjustable main current source to provide a signal that can be compensated. This allows a wide range of absolute output values.
Cascoding has to be used in all circuit components to reduce the power supply dependence of the circuit.

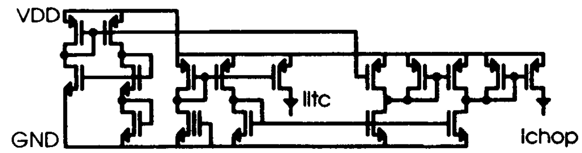

Fig. 1: Circuit diagram of htc source, ltc source and pwl-sigmoid circuit

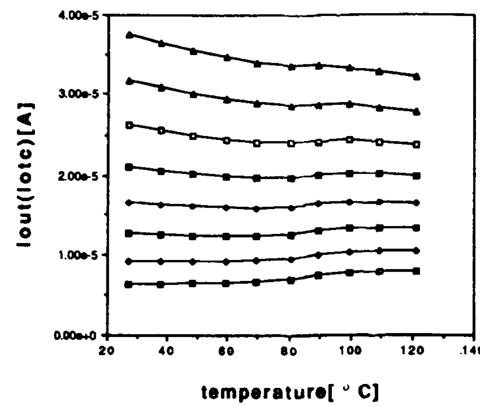

Fig. 2: Output current of ltc source for various floating gate charges

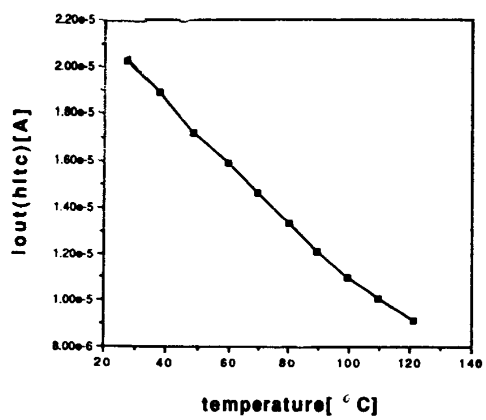

Fig. 3: Measured output current of htc source

Adjustments

The adjustment procedure will be explained with the circuit used in the simulations, because its design allows a simple systematic non-iterative procedure. The starting point is a measurement of the active region of a module. Due to the usual parameter fluctuations more modules than actually required should be provided. Since the transfer-function of the weight circuit is zero above a certain temperature, the adjustment procedure is started slightly above the turn-on temperature of the first module. The main EEPROM is adjusted for the target value. Now the temperature has to be reduced to the center of the gain region of this module and its weight adjusted for the target value. The reduction of temperature and subsequent adjustment have to be repeated for every module.

The weight adjustment is done in the following manner: Starting with a high programming voltage for each direction, the appropriate pulse for increasing or decreasing the threshold voltage is applied. If an overshoot over the target value occurs after one pulse, the programming voltage is decreased. Thus the changes in floating gate charge get smaller and more accurate adjustments can be performed. After about 20 pulses 10mV accuracy in threshold voltage can be easily achieved.

Results

A three neuron version of the circuit was implemented. The resulting output curves are shown in fig. 6. The reference-source was programmed for three different output values of 6.7µA, 8.7µA and 10.4µA. In the range from 45C^{o} to 75^{o}C a deviation of less than 2% of the target value was observed. In this region only two neurons were active. Higher deviation at lower temperature is due to the low number of neurons. Besides the low number of neurons the circuit had two other design flaws: The temperature coefficient of the weight circuit dominated the sigmoid signal and the temperature coefficient of the Itc-source had a different sign for different parts of the curve requiring bi-directional weights.

A simulation of a circuit with 6 neurons showed the following results: It was adjusted for a temperature stable reference current of 100µA. The stability is 1.5% over a range of 5 to 100^{o}C. The output of individual modules and their sum is shown in fig. 7. An extension of range simply requires more modules. This value can be achieved independent of fluctuations in model parameters. Also other values can be achieved, limited by the dynamic range of the main EEPROM and its maximum temperature coefficient, which must not exceed the output current of the modules.

It was also adjusted to approximate an arbitrary function, here a straight line given by

$$I_{out} = 0.75\tfrac{\mu A}{K} * T - 75\mu A$$

The simulated deviation is less than 3µA (fig. 8).

The ability to approximate a function over temperature can be used for other purposes than compensation of gradients. A temperature dependent bias to achieve temperature stability of another parameter can be generated. The use of a temperature dependent bias current will be illustrated with the example of a differential pair. A differential pair allows the adjustment of the transconductance parameter g_m with the bias current I_{bias} according to

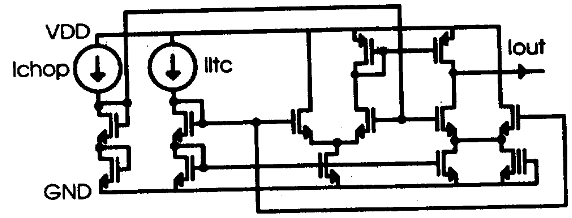

Fig. 4: Circuit diagram of the weight circuit. The weight is stored on the floating gate.

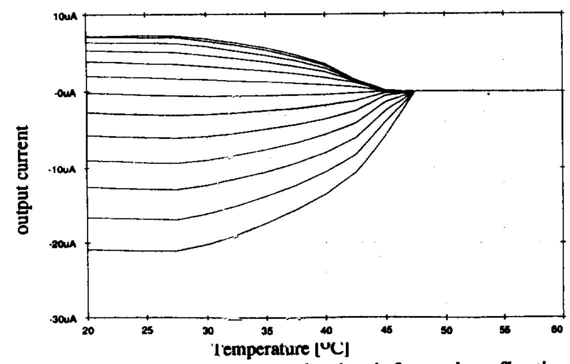

Fig. 5 Output current of the weight circuit for various floating gate charges.

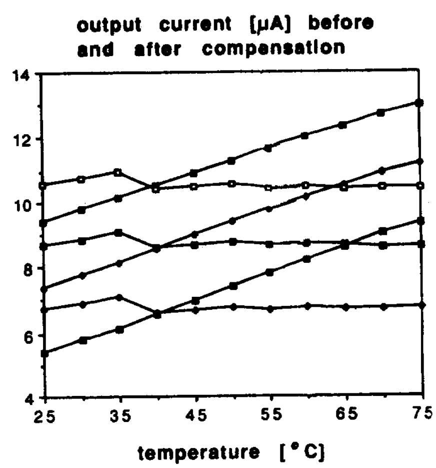

Fig. 6: Measured output from a 3 module implementation before and after compensation. 2% accuracy for a temperature range of 45 to 75^{o}C.

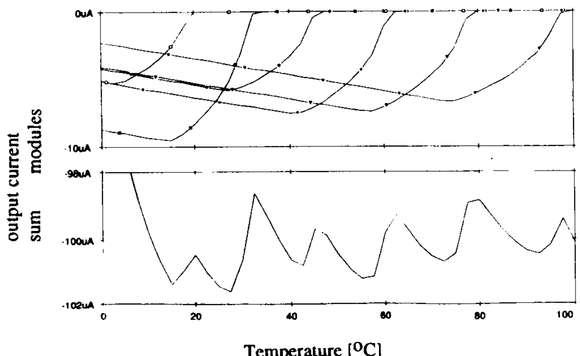

Fig. 7: output current of 6 neuron circuit, programmed for a constant output of 100μA. 1.5% accuracy from 5 to 100°C.

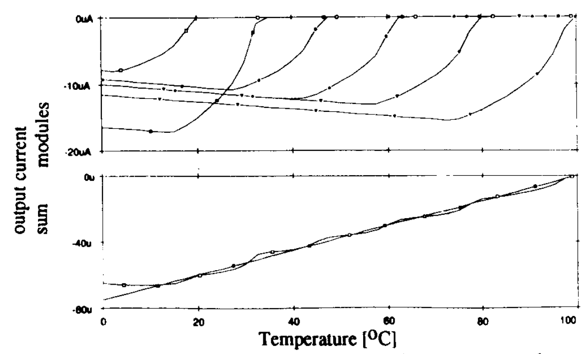

Fig. 8: output current of 6 neuron circuit, programmed to approximate a straight line.

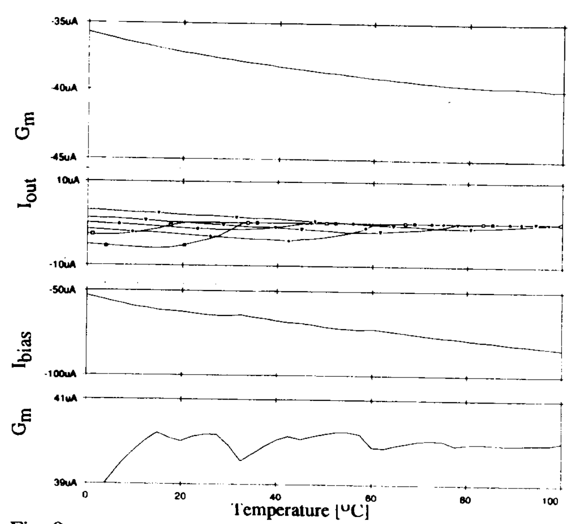

Fig. 9: output current of 6 neuron circuit, programmed for a constant transconductance of 400μA/V. G_m before trimming, module output, bias current, G_m after trimming. 1% accuracy from 5 to 100°C.

$$g_m = \sqrt{\beta * I_{bias}}$$

β is the transconductance parameter of the MOSFET and is temperature dependent,

$$\beta = f(T).$$

With

$$I_{bias} = f^{-1}(T),$$

the transconductance value of the differential pair is constant over temperature. A simulation result is shown in fig. 9. A transconductance value of 400μA/V was maintained to within 1% using temperature dependent biasing.

Conclusion

This is the first reported reference implementation based on EEPROMs. Its ability to provide a programmable output current is unique. A temperature variation below 2% over a temperature range from 45°C to 75°C hints at its possibilities after the existing flaws in the implementation are worked out. Simulations of an improved circuit show that 6 modules allow about 1.5% accuracy over a range from 5 to 100°C. The flexibility of this circuit to compensate for temperature dependence in a circuit is a unique feature with a wide range of applications. The temperature dependence of many circuits could be reduced. Another possible application is the generation of temperature signal of well defined shapes.

The question remains, whether analog storage is suitable for a reference, since digital storage of weights is more robust. High temperature and radiation are known to increase charge leakage from the floating gate. Application in these environments is impossible. Around room temperature leakage will cause negligible effects for several years.

References

[1] Y.P.Tsividis and R.W.Ulmer, "A CMOS Voltage Reference," *IEEE J. Solid-State Circ.*, vol. SC-13, pp. 774-778, 1978

[2] G.Nicollini and D. Senderowicz, "A CMOS Bandgap Reference for Differential Signal Processing," *IEEE J. Solid-State Circ.*, vol. SC-26, pp. 41-50, 1991

[3] W. M. Sansen, F. Op't Eynde, and M. Steyaert, "A CMOS temperature compensated current reference," *IEEE J. Solid-State Circuits*, vol. SC-23, no. 3, pp. 821-825, June 1988

[4] J. Sweeney, R. Geiger, "Very high precision trimming using floating gate MOSFETs, " European Conf. on Circuit Theory and Design, Brighton UK, September 1989

[5] A.Thomsen and M.A.Brooke, "A floating gate MOSFET with tunneling injector fabricated using a standard double polysilicon CMOS process," *IEEE Electron Device Letters*, vol. EDL-12, no. 3, pp. 111-113, 1991

[6] Z. Wang et al., "Adjustable bi-directional MOS current mirror/amplifier," *Electronics Letters*, v. 25, no. 10, pp. 673-675, May 1989