Design for MOSIS Education Program

(Research)

T46C-AE

<u>Project Title</u>

Low Voltage Analog Building Block

Prepared by: C. Durisety, S. Chen, B. Blalock, S. Islam

Institution: Department of Electrical and Computer Engineering,
University of Tennessee, Knoxville, TN–37996-2100

Introduction

The purpose of this project is to explore various circuit techniques in developing the low voltage analog building blocks such as operational amplifiers and voltage reference. An operational amplifier employing circuit techniques of ‘super transistor’ [3] and ‘regulated cascode transistor’ [7] was fabricated, along with a curvature-compensated bandgap voltage reference. Using TSMC 0.35 μm double-poly process, both circuits aimed to operate low than standard supply voltage (3.3 V). The opamp was targeted for as low as 2.5V, and the bandgap architecture was compatible for sub-1V operation. This fabrication run helps the authors in better understanding low voltage circuit techniques to develop ultra-low voltage designs in the future.

Project Description

Opamp

Figure 1 shows the schematic of the operational amplifier based on the “composite transistor” introduced by Coban et. al [3]. One of the common methodologies to achieve higher gain in an opamp is to use the regulation amplifier for amplifying the output impedance. But this is proven to be very inefficient both in area and power. As shown in [3], the composite transistor can be used as a regulation amplifier instead of a complete opamp. This technique is efficient in area and in power since it consists of only 4 transistors. The gain offered by the regulation amplifiers can be achieved by increasing the transconductance (gm) of the common source transistor. Large output swing can be achieved with this amplifier by appropriately biasing the transistors connected to the rail in the folded cascade branches in triode region. The composite transistors are high-lighted in the Figure 1. An external current reference is required for the functionality of this amplifier. The external load capacitance acts as the compensation capacitance.

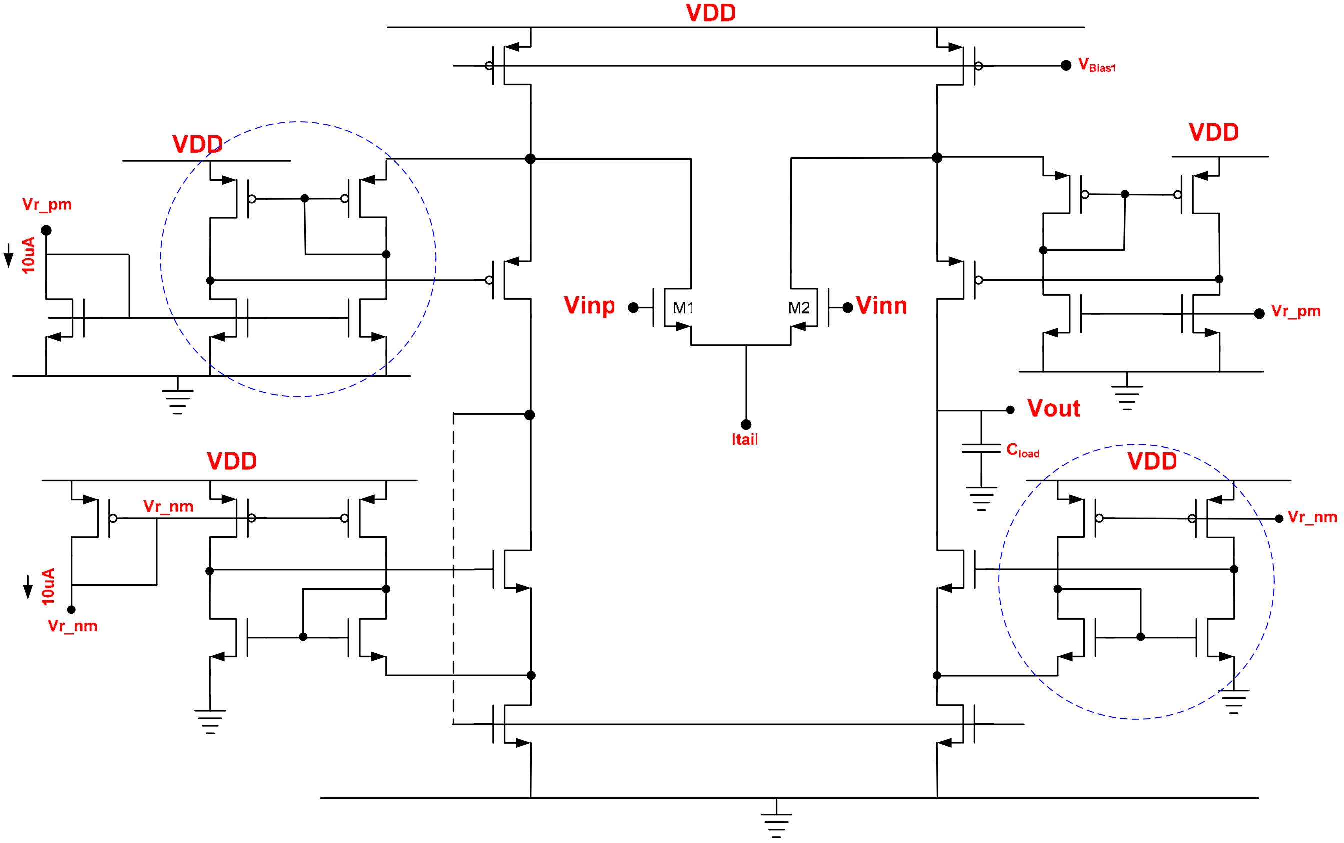


Figure 1 Simplified schematic of the Operational Amplifier

Curvature-bandgap reference

Figure 2 shows the simplified schematic of the designed bandgap voltage reference. The selection of this architecture ensures the circuit correctly functioning in lower supply voltage. Due to the non-linear nature of the diode voltage, V_{BE}, output voltage exhibits non-linearity across temperatures. Various curvature compensation techniques have been reported in literature. The technique by P. Malcovati [1] is used here for its effectiveness and simplicity. In order for clear identification of the effect by curvature-compensation circuitry, external connection is used to enable and disable the curvature-compensation.

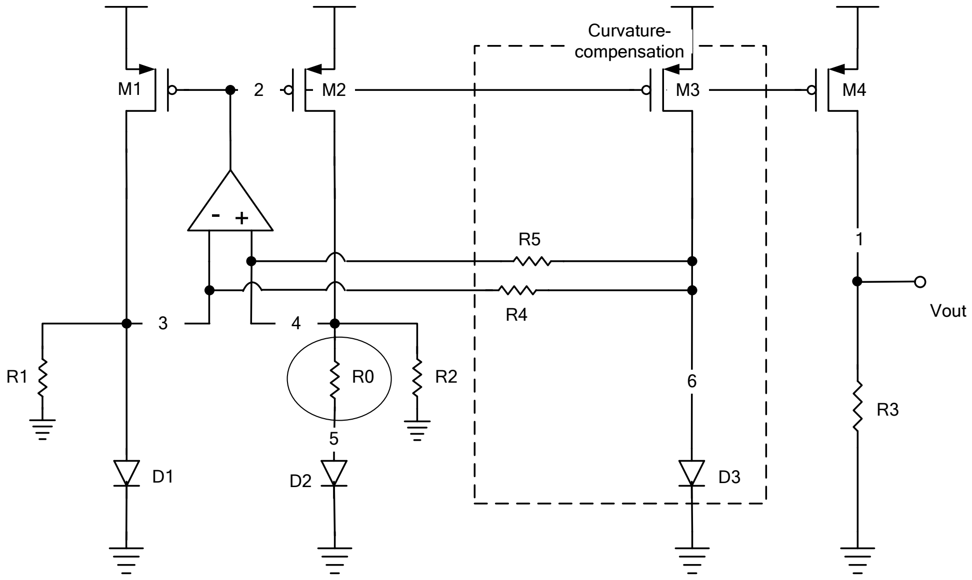


Figure 2 Schematic of the bandgap

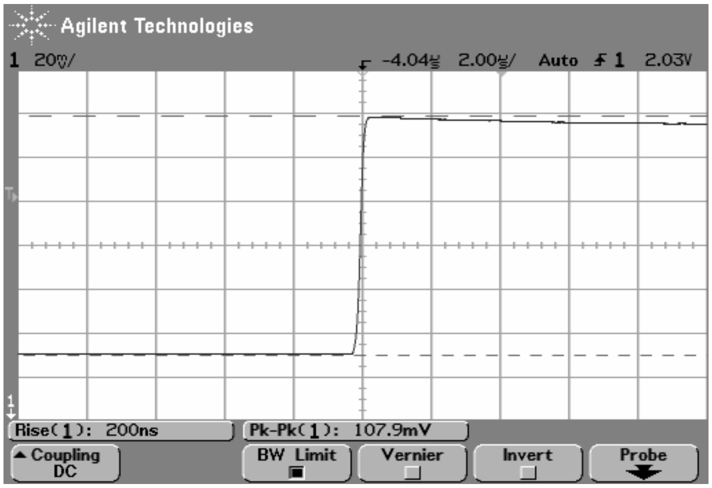
Test and Characterization

Opamp

The basic characteristic features of the opamp like open loop gain, unity gain band width, offset, slew rate, Input common mode range are measured and are compared with the simulation results. Measurement results have been obtained on a randomly selected set of 5 chips. Following table compares the above discussed parameters between measurement results and simulation results. The best measurement results are used in the following table.

Parameter	Simulation Result	Measurement Result
Open loop gain	74dB	81dB
Unity Gain Bandwidth	~4.7MHz (Cl = 20pF)	6MHz (Cl = 20pF)
Rise time (small signal)	120 ns	200ns
Fall time (small signal)	120 ns	148ns
Phase Margin	80º @ Cload = 20pF	~90º @ Cload =20pF
Slew Rate (1V pk-pk)	0.26V/µsec	0.27V/µsec
ICMR	0.5V – 3.0V	0.5V – 3.0V
Offset	-	1.02mV

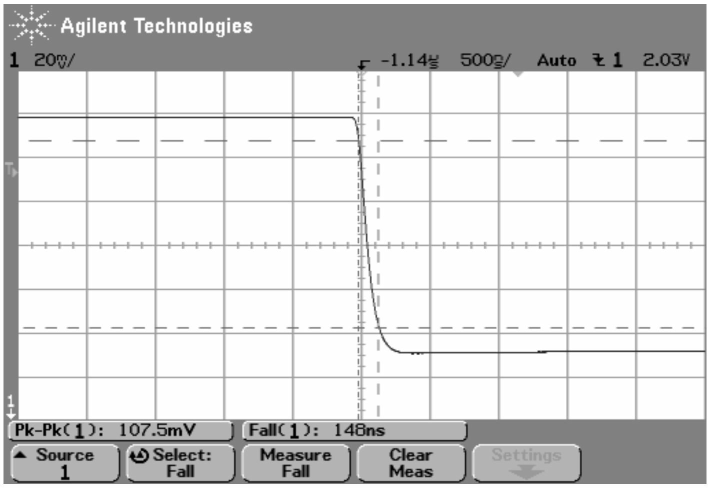
Small signal rise and fall times are measured for a 100mV p-p input signal at 1 KHz, with Cl = 20pF. The variation in the unity gain bandwidth and the open loop gain could be attributed to the different process variations. A 1V pk-pk signal is used for the slew rate measurement result. Unity gain feedback configuration was used for measuring the slew rate, rise and fall time results. Slew rate and small signal measurement results are shown in Figures 3-5. There is a good match between simulation and measurement results.



1 20mV/ -4.04µs 2.00µs/ Auto 1 2.03V

Rise(1): 200ns Pk-Pk(1): 107.9mV

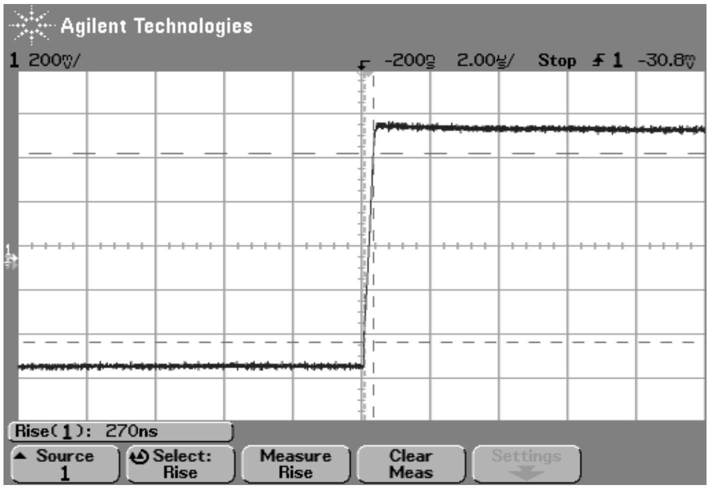
Figure 3 Measurement result for the rise time



1 20mV/ -1.14µs 500ns/ Auto 1 2.03V

Pk-Pk(1): 107.5mV Fall(1): 148ns

Figure 4 Measurement result for the fall time



Rise(1): 270ns

Figure 5 Measurement result for the slew rate

Curvature-compensated BGR

Temperature testing is the main part of the bandgap characterization effort. The nominal output voltage is 850 mV at room temperature. The output voltage with and with curvature compensation versus temperature from 3 representative samples are shown below. Figure 6 shows a best case in which the TC of the output voltage is less than 10 ppm/°C with curvature-compensation and the TC is around 300 ppm/°C without. Figure 7 and Figure 8 show the improvement to the temperature behaviors with curvature-compensation compared to without, which lowered the TC from 300 ppm/°C to around 100 ppm/°C.

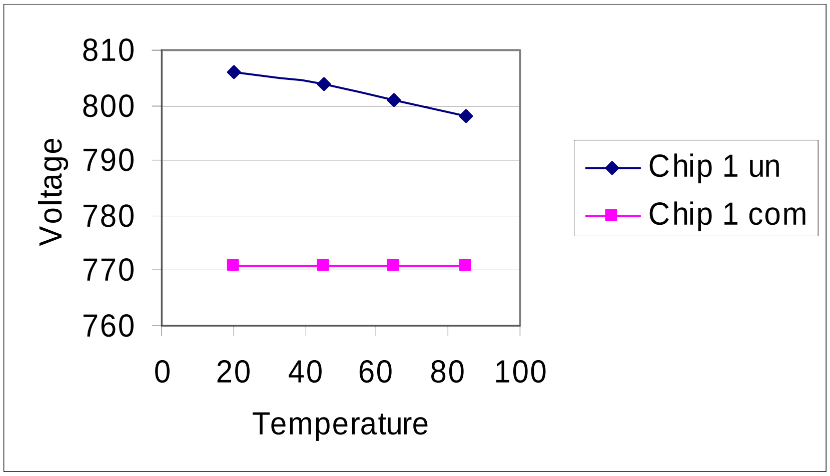


Figure 6 Output voltage vs. temperature (chip1)

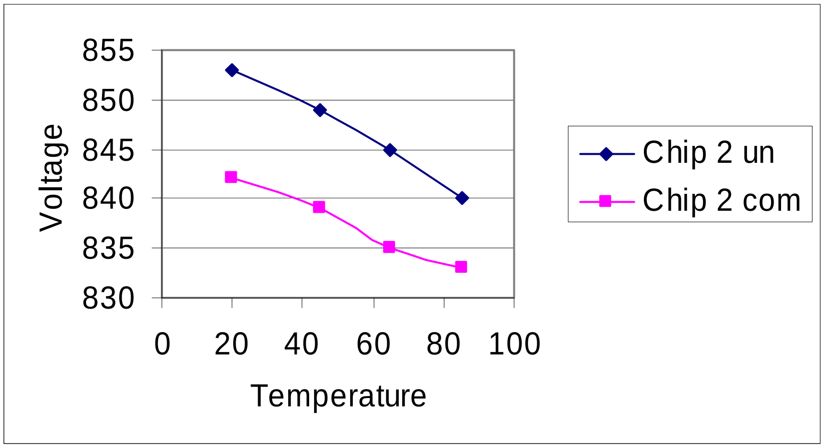


Figure 7 Output voltage vs. temperature (chip2)

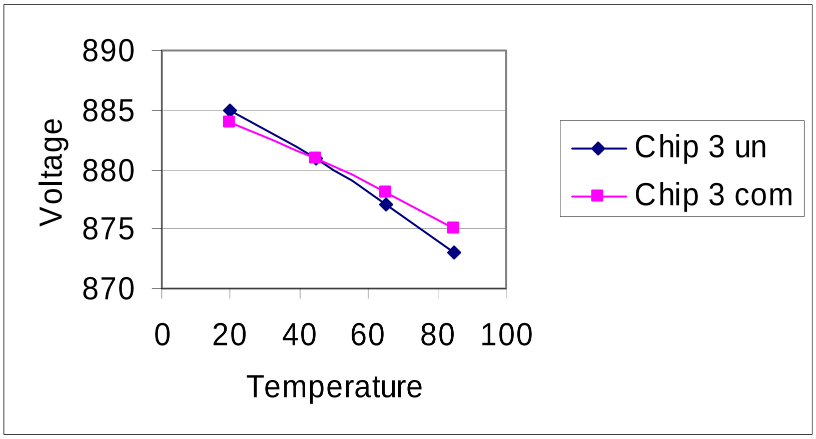
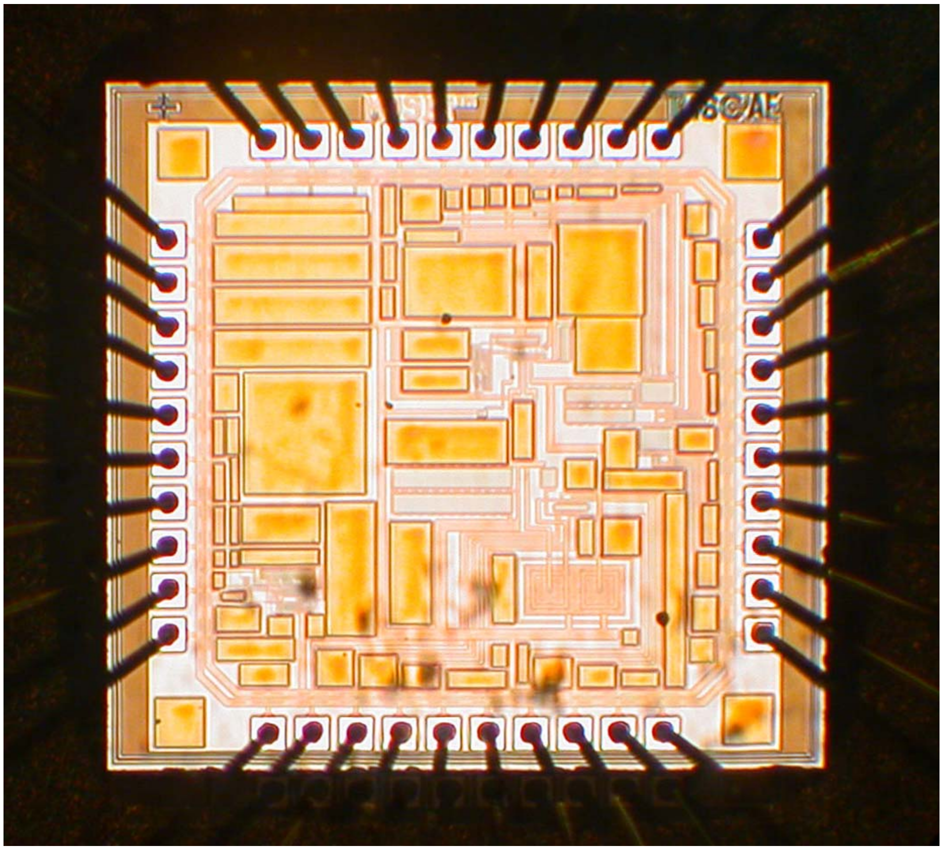


Figure 8 Output voltage vs. temperature (chip3)

The bandgap architecture adapted in this design enables sub-1V operation, however in the same time, it created new problem. In standard bandgap circuit, there are two well-defined operational-points. In this design, with the two additional resistors, the operational points are very hard to define. In another word, the state of normal operation is much more difficult to maintain. The start-up circuit used in this design is power-on startup, which will be turned off after the circuit is started. This becomes a problem when the circuit goes out of the normal operation mode when the circuit is powered on, because the power-on startup won't recover the normal operation unless reset the power.

Chip picture



Conclusions

Both the designs opamp and the bandgap have been characterized and the measurement results are shown. The results show fairly good match between simulation and measurement results for the opamp and the bandgap reference. The authors are analyzing the differences in small signal rise and fall times and also their differences between simulation and measurement results. The concept of sub-1V curvature compensating bandgap reference is proved, while some improvements on the startup circuit are needed in the future revision.

Reference:

[1] P. Malcovati, “Curvature-Compensated BiCMOS Bandgap with1-V Supply Voltage”, *IEEE J.Solid-State Circuits*, vol.36, 2001

[2] R.G.H.Eschauzier et al., “A programmable 1.5V CMOS class-AB operational amplifier with hybrid nested miller compensation for 120dB gain and 6MHz UGF,” *IEEE J. Solid-State Circuits*, vol. SC-29, pp.1497-1504, Dec. 1994.

[3] Coban, A.L. and Allen, P.E., “A 1.75V rail-to-rail CMOS op amp,” *IEEE International Symposium on Circuits and Systems*, 1994, vol. 5, pp.497-500.

[4] Sackinger E et al., “A high-swing, high-impedance MOS cascode circuit,” *IEEE J. Solid-State Circuits*, vol. 25, no. 1,pp.289-298, Feb. 1990.

[5] Minch .B, “A low-voltage MOS cascode bias circuit for all current levels,” *IEEE International Symposium on Circuits and Systems*, vol. 3, May 2002.

[6] Zhiwei D. et al., “Low-voltage, supply independent CMOS bias circuit,” The *2002 45th Midwest Symposium on Circuits and Systems*, vol. 3, Aug. 2002.

[7] Lu G.N et al., “1.3V single-stage CMOS opamp,” IEEE Electronic Letters, vol.34, no. 22, Oct. 1998.