Inflection Point Correction for Voltage References

Kee-Chee Tiew, Jim Cusey*, Randall Geiger

Department of Electrical and Computer Engineering, IOWA STATE UNIVERSITY, Ames, IOWA 50011, USA
*Dallas Semiconductor, Dallas, TEXAS, USA

Abstract- A self-calibration technique that corrects the inflection point of the reference voltage curvature is presented. This technique employs lattice-heating effect of semiconductor to change the operating temperature of the circuit. By sampling the reference voltage at two temperatures, the inflection point of the reference voltage curvature is first estimated and then corrected if necessary. The implementation was verified through simulation, and the results are attractive for achieving optimal first-order voltage references.

Introduction

The basic operation of first-order voltage references relies on the temperature compensation of the base-emitter voltage with a proportional-to-absolute temperature (PTAT) voltage source [1], as depicted in Figure 1.

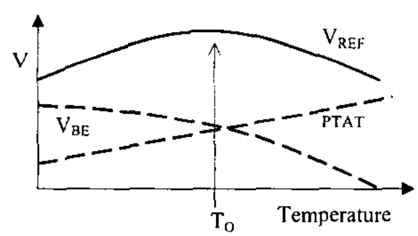

Figure 1: First-order voltage references

The temperature slope of the PTAT voltage source is chosen such that the linear temperature dependence of V_{BE} at T_O is cancelled. In other words, T_O is the inflection point of the V_{REF} curve because the tangent line of the curve at T_O has zero derivative. If the PTAT slope is insufficient, the inversely-proportional-to-absolute temperature (IPTAT) behavior of V_{BE} will dominate and consequently the inflection point will shift towards lower temperature. Similarly, the opposite happens when the PTAT slope is overly chosen, as depicted in Figure 2. By carefully placing the inflection point with the proper PTAT slope, one can realize a first-order voltage reference with minimum voltage error, Δ_1, compared to Δ_2 and Δ_3. Nevertheless, the inflection point is subject to process variation despite the designer's effort of choosing the appropriate PTAT. One common way of correcting the inflection point is to add a postproduction measuring and calibrating step [2], which requires thermo-cycling the parts. However, this method is slow and expensive. Therefore, a self-calibration technique that corrects the inflection point of the reference voltage is proposed.

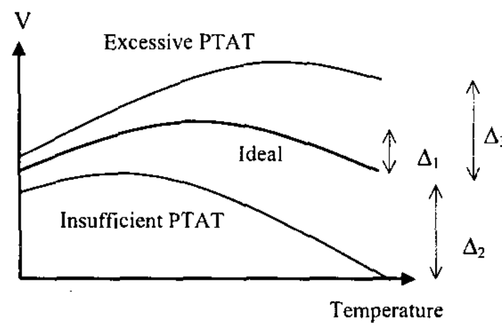

Figure 2: Voltage references with different PTAT

On-chip Heater

In order to take measurements from the circuit at different temperature but without having to go through the thermo-cycle in oven, an on-chip heating mechanism is needed to heat up the circuit. For this purpose, high current Bipolar Junction Transistors (BJT) are used as on-chip heaters. The strategy is to place some high current BJT in close proximity with the temperature sensitive core of the voltage reference circuits, for example the BJT pair in a bandgap voltage reference circuit as in Figure 3, and turn on the high current BJT so that the heat dissipated by the BJT will affect the operating temperature of the reference circuit. To further investigate the lattice heating mechanism of semiconductor, two high current BJT were simulated using Silvaco Atlas. Two NPN transistors were constructed with 20um spacing between each other. Refer to Figure 4 for the cross sectional diagram. The ambient temperature was 300K. A 1.8V step was applied to both bases of the BJT at time t=0, and the thermal transient response of the structure was studied. There was about 6mA of current flowing into the base of each BJT. The structure reached thermal equilibrium after 500us. From Figure 5 and 6, it is shown that the temperature at the region between the BJT is around 340K at equilibrium. If the BJT pair of a bandgap voltage reference circuit is placed in the region between the heaters, the effective operating temperature of this bandgap

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voltage reference circuit is about 40K above the ambient temperature. Note that it is a local heating mechanism, for a circuit's operating temperature is affected if it is closely placed to heaters but unaffected is it is far apart.

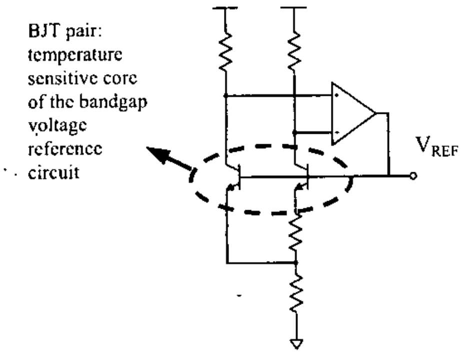

Figure 3: Bandgap voltage reference circuit

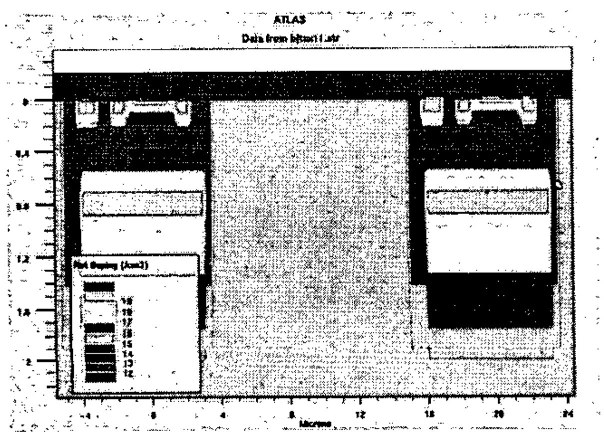

Figure 4: Cross section of the BJT heaters

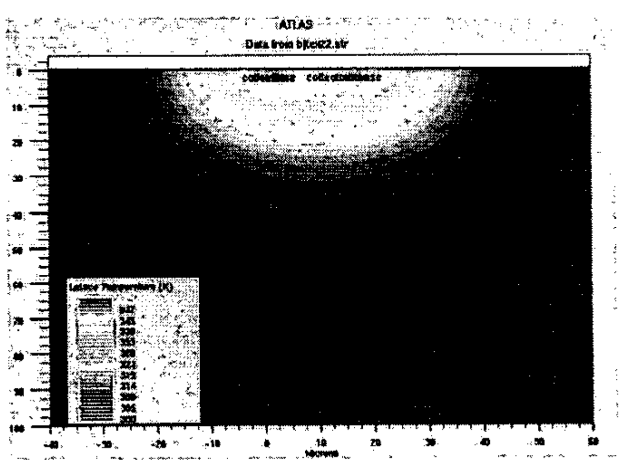

Figure 5: BJT heaters at thermal equilibrium

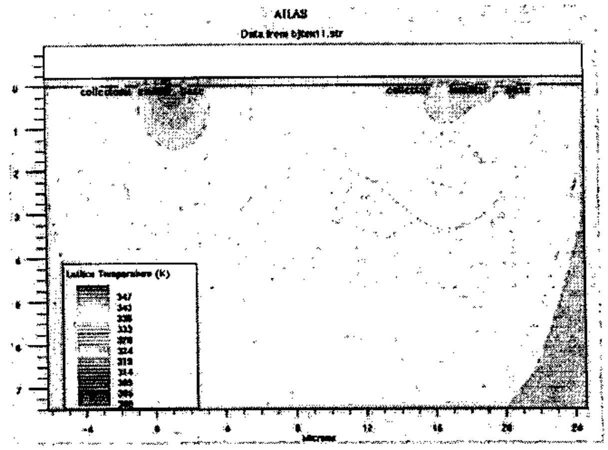

Figure 6: (Zoom in) BJT heaters at thermal equilibrium

Inflection point correction

Refer to the bandgap voltage reference circuit in Figure 7. Each resistor in the switched-resistors array is sized such that the output reference voltage (V_{REF}) will have different inflection points for different closed switch. Refer to Figure 8. The purpose of having the switched-resistors array is to introduce redundancy such that one of the curves can still attain the correct inflection point despite process variation.

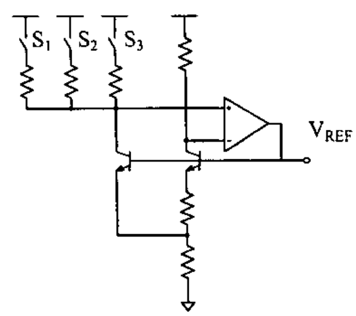

Figure 7: Bandgap voltage reference circuit with configurable resistors

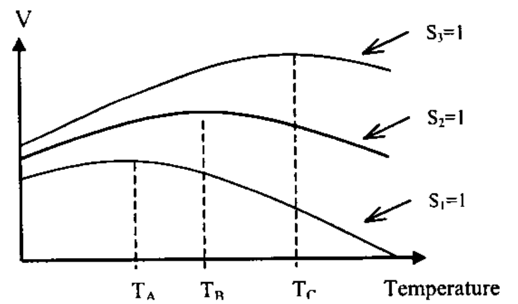

Figure 8: Output reference voltage curves with different inflection point

Next, the curve with the correct inflection point is identified with a search algorithm. Refer to Figure 9 for the flow diagram of the search algorithm. First, an A/D conversion is performed at ambient temperature, T_i, using the dummy reference as input and the bandgap circuit as reference voltages. One A/D conversion is performed for each configuration of the bandgap circuit. The conversion results are then stored in the memory. The dummy reference is not a critical part, and it can be easily constructed with a simple diode connected NPN driving a resistor load. Then, the on-chip heater is turned on to heat up the BJT pair in the bandgap reference circuit to a higher temperature, $T_i+\Delta T$, and the system waits until thermal equilibrium is reached. Note that the heating only affects the bandgap circuit since its BJT pair is placed closely to the heaters while the dummy reference is placed far apart from the heaters. When equilibrium is reached, the system performs another A/D conversion for each configuration of the bandgap circuit. But this time, the first set of data is recalled from the memory to compare with the new set of conversion results. If the first reading matches the second reading as the configuration of the bandgap circuit is being cycled through, then there is an inflection point between T_i and $T_i+\Delta T$ because the only way to have the identical conversion result is to have the identical reference voltage before and after the heating. Refer to Figure 10 for graphical illustration.

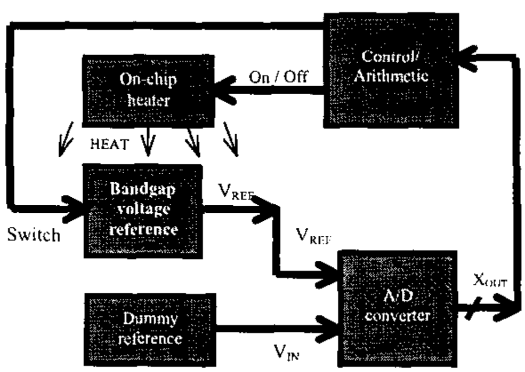

Figure 9: Flow diagram of the search algorithm

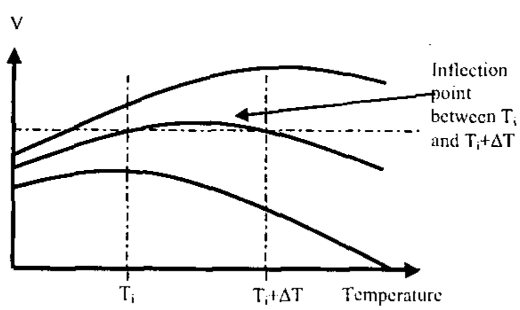

Figure 10: Locating the inflection point

For commercial temperature range that is between -40°C and 100°C, the ideal inflection point is around 30°C but this may vary from one process to another. Hence, the correction technique presented here can be applied at room temperature.

Implementation

The circuit depicted in Figure 7 has been implemented in AMI 1.5μ process. The size of the resistors array is 16. The A/D converter, control logic and arithmetic unit were modelled with spectre AHDL for simulation purposes. The system was simulated using spectre.

Simulation results

The bandgap voltage reference circuit was designed to have an inflection point at 30°C. The resistors in the circuit was scaled by multiplying all resistors with a constant greater than 1 to emulate the process variation effects, which resulted in shifting the inflection point from the ideal location towards lower temperature. Refer to Figure 11a. Figure 11b depicts the results after the correction technique was applied. The voltage deviation before correction is 3.07mV, and it drops to 1.01mV after correction.

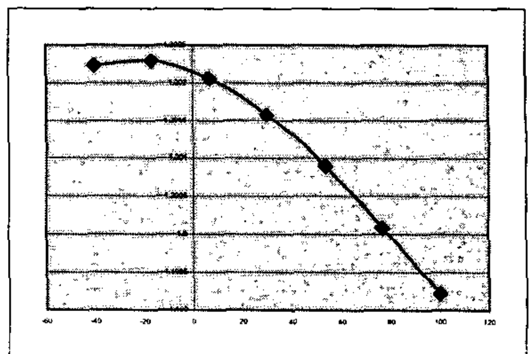

Figure 11a: Inflection point error (insufficient PTAT)

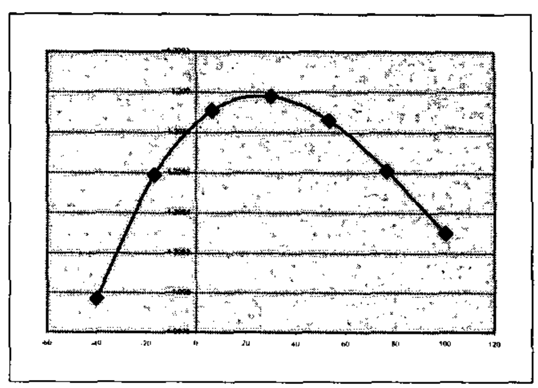

Figure 11b: Inflection point error corrected

Another simulation was performed for resistor scaling factor less than 1. The pre-correction temperature behavior is depicted in Figure 12a, and Figure 12b is the post-correction result. The voltage deviation before correction is 3.71mV, and it drops to 0.79mV after correction.

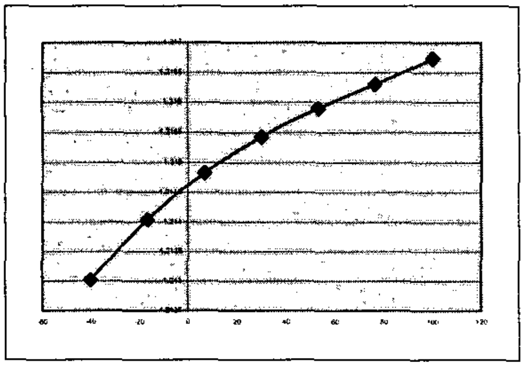

Figure 12a: Inflection point error (excessive PTAT)

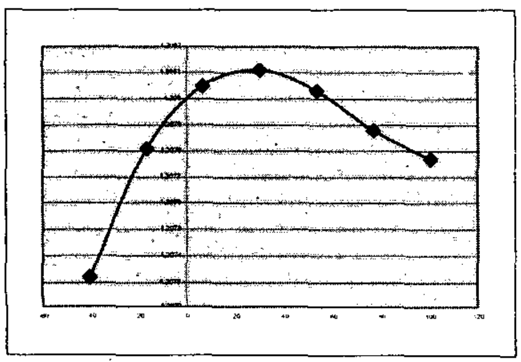

Figure 12b: Inflection point error corrected

Discussion

In the simulation, the only process variation that was considered was the deviation of resistor doping. However, other process variations will manifest in the same manner as the resistor doping deviation does, which is the shifting of the inflection point away from the ideal location. Therefore, the size of the resistor array in the bandgap voltage reference circuit should be chosen to account for all combinations of process variations.

Conclusion

An inflection point correction technique was presented together with its implementation and simulation results. This technique is cheap and practical because it is self-calibrated. Moreover, this technique can be programmed to operate upon power up, which will further shorten the rush to market time.

References

[1] G. A. Rincon-Mora, *Voltage References*, John Wiley & Sons, 2002.

[2] A. Buck, C. McDonald, S. Lewis, T. R. Viswanathan, "A CMOS bandgap reference without resistors," *IEEE Journal of Solid State Circuits*, vol.37, no.1, pp.81-83, Jan 2002.