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An Accurate Voltage Reference For Automotive Applications

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Abstract:
This article compares different topologies of simple accurate bandgap voltage references. The proposed topologies are the Brokaw bandgap reference and CMOS bandgap reference in two variants with NPN bipolar core and with PNP bipolar core. For automotive applications with wide temperature range and very low power consumption was selected the CMOS type of bandgap reference with PNP transistors which can be realized in bulk CMOS process. The selected bandgap cell was calculated and designed in automotive 180 nm CMOS technology. Calculations were compared with circuit simulations using Spectre simulator.

INTRODUCTION

The design for automotive industry is specific due to its operation in harsh environment. The main challenges in comparison to consumer electronics designs are much wider temperature range from -50 °C up to 200 °C, immunity to supply variations and disturbances, immunity to substrate currents and low power current consumption. The voltage reference is not only a temperature compensated voltage source but also a transiently stable circuit, where the output is impervious to sudden variations in supply voltage, noise and manufacturing process.

There are many articles focusing on the temperature dependence analysis of voltage references but usually with limited temperature range beginning at -50 °C and going up to 125 °C [1], [2], [3]. At this limited temperature range the reachable TC are tens of ppm/°C, with some more advance techniques the levels around 2 ppm/°C are reachable. These very low temperature variations are paid by higher current consumption and higher supply voltage requirements.

In automotive industry the typical operating range for junction temperature is up to 150 °C and for high-power system on chip (SoC) applications junction temperature goes above 175 °C close to 200 °C. Voltage references going to such high temperatures are often using advance compensation techniques typically based on measurement of temperature and feeding correction voltage/code to the voltage reference generator. This paper is not focused on such kind of compensations.

Modern automotive voltage references in sub-micron technologies are also limited by supply voltage where the reference has to be parametric from 2 V and functional from 1.5 V to support fluctuating battery supplies. The current consumption requirements for SoC voltage reference are around 100 uA for complete block going down to range from 5 to 10 uA supporting power-saving and sleep modes of the systems. Taking into account the above mentioned limitations the following criteria were selected for the analysis of the basic bandgap voltage reference topologies: stability over wide temperature range from -50 °C to 200 °C, stability of block supply voltage over range from 2 V to 3.6 V and the complete block current consumption less than 100 uA.

BANDGAP VOLTAGE REFERENCES

Brief theory

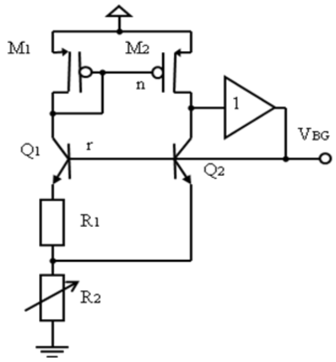
In CMOS process are mainly used bipolar transistors in the bandgap voltage reference core. MOS transistors in sub-threshold region are used in automotive designs very rarely due to their weakness in noise immunity. A substrate PNP can be made in bulk CMOS processe, lateral PNP or vertical NPN devices are used in more complex CMOS processes. Basic equations are the same for both types of bipolar transistors (BJT). Some differences are there - mainly in electrical parameters or sensitivity at packaging.

General purpose of bandgap voltage references is generating stable voltage over temperature, supply voltage and process spread but majority of characteristics is temperature dependent in CMOS processes. With BJT we can generate proportionally dependent voltage PTAT and complement of this voltage CTAT. CTAT voltage is equal to V_{BE} of bipolar transistor and PTAT voltage is equal to multiple of ΔV_{BE} between two BJT working under different current densities. Bandgap voltage is sum of the PTAT and CTAT.

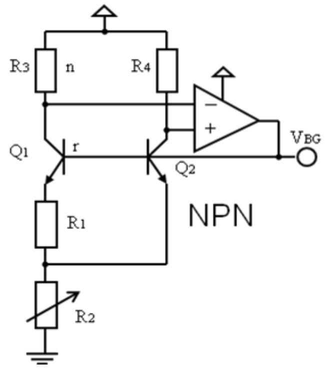
$$V_{REF} = V_{CTAT} + V_{PTAT} = V_{BE} + \alpha \cdot \Delta V_{BE} \qquad (1)$$

Basic topologies

There are several topologies of voltage references.



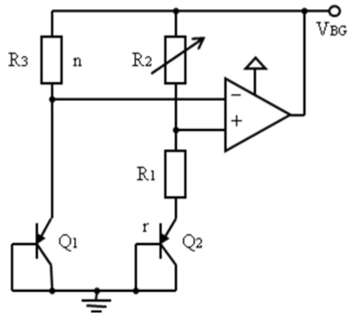
a)



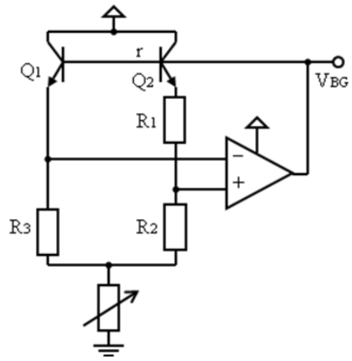
b)

Fig. 1: Topology of Brokaw bandgap cell a) with current mirror, b) with operational amplifier.

For example the topology of the Brokaw bandgap cell with MOS current mirror is depicted in Figure 1a). Instead of current mirror there can be used operational amplifier with combination of resistors as depicted in Figure 1 b).
This type of bandgap cell is widely used due to its simple topology and small impact of operational amplifier offset on output reference voltage. Negative aspects are that this bandgap cell needs leakage current compensation for temperatures higher than 150 °C and bigger current consumption (typically around 100 uA) [4]. These two negative aspects were reasons why this topology was not selected in this work for deeper analysis.



a)



b)

Fig. 2: Topology of CMOS bandgap cell with a) PNP bipolar transistor core, b) NPN bipolar transistor core

Other topology of voltage reference cell which is widely used is CMOS reference. This voltage reference topology can be designed in two variants with NPN bipolar core and with PNP bipolar core shown in Figure 2. This type was selected for its usage in very low power consumption circuits. The variant with PNP bipolar core is analyzed in this work.

CALCULATION VERSUS SIMULATION OF PNP BANDGAP CORE

Basic equations for bipolar transistor:
collector current [5]

$$I_C = I_S \cdot e^{\left(\frac{q \cdot V_{BE}}{k \cdot T}\right)} \qquad (2)$$

base to emitter voltage

$$V_{BE} = \frac{k \cdot T}{q} \cdot \ln\left(\frac{I_C}{I_S}\right) \qquad (3)$$

where $kT/q = V_T$ is thermal voltage (25.9 mV at 300 K) and I_S is saturation current which is strongly temperature dependent, causing that the V_{BE} has negative temperature coefficient, providing the CTAT voltage.
The first step during design of bandgap core is definition of voltage drop over resistor R_1. This voltage ΔV_{BE} together with R_1 resistor value defines current consumption and operating point of the bandgap core. The voltage ΔV_{BE} is generated by different current densities of bipolar transistors Q_1 and Q_2. In the calculations later the different current densities are set by different bipolar emitter currents I_{E1} / I_{E2} = r and also by different base-emitter junction areas $A_2 / A_1 = n$ in line with Figure 2 a).
By using (3) can be derived:

$$\Delta V_{BE} = V_{BE1} - V_{BE2} = \frac{k \cdot T}{q} \cdot \ln\left(\frac{J_{C1}}{J_{C2}}\right) \qquad (4)$$

where $J_C = I_C / A_E$ which is current density on the base-emitter junction

In our case the selected bipolar emitter current ratio r = 3 and selected base-emitter junction area ratio n = 8 the calculation results to equation

$$\Delta V_{BE} = \frac{k \cdot T}{q} \cdot \ln(r \cdot n) \qquad (5)$$

Calculated ΔV_{BE} = 82 mV for T = 300K.

The complete temperature characteristic of calculated ΔV_{BE} is shown in Figure 3. In the same figure the calculation was compared with simulation in Spectre simulator using automotive 180 nm CMOS technology models.

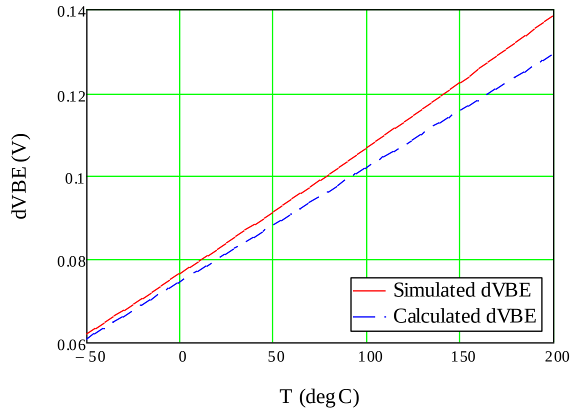


Fig. 3: Comparison of ΔV_{BE} simulated and calculated by equation 5.

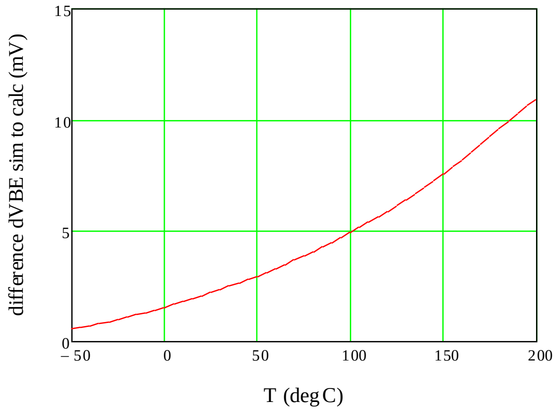


Fig. 4: Difference of ΔV_{BE} simulated to calculated.

The above results show that above used calculation of ΔV_{BE} is not correct. For correct and precise design of voltage reference more exact equation for ΔV_{BE} calculation has to be used.

In analyzed configuration the base resistance, emitter resistance and beta of bipolar transistor have to be taken into account. Then the equations (3, 4 and 5) are updated:

$$V_{BE} = I_E \cdot \left(\frac{R_B}{\beta + 1} + R_E\right) + \frac{k \cdot T}{q} \cdot \ln\left(\frac{I_E}{I_S}\right) \qquad (6)$$

where I_E is bipolar transistor emitter current, R_B is base resistance, R_E is emitter resistance, β is beta of bipolar transistor which is temperature dependent with positive temperature coefficient. The R_B, R_E, β are device and process specific parameters and for further calculations are taken from technology manual. Finally the ΔV_{BE} equation is updated to:

$$\Delta V_{BE} = \frac{k \cdot T}{q} \cdot \ln(r \cdot n) + I_{E1} \cdot \left(\frac{R_B}{\beta + 1} + R_E\right) - I_{E2} \cdot \left[\frac{R_E}{r} + \frac{R_B}{r \cdot (\beta + 1)}\right] \qquad (7)$$

From the (7) is visible that the ΔV_{BE} and in consequence PTAT voltage are now dependent on absolute value of forced current trough the bandgap core.
The emitter current throuh the transistor Q1 from Figure 2 a) was selected 3 uA at temperature 50 °C. The current through the second transistor is defined by resistor ratio $R_3 / R_2 = r = I_{E1} / I_{E2}$. Temperature dependency of emitter current is visible on next figure.

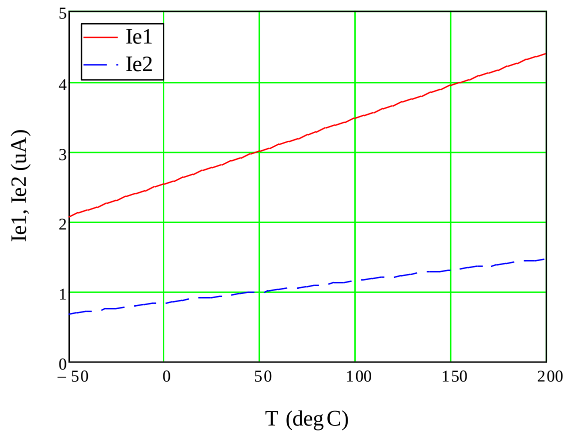


Fig. 5: Emitter current temperature dependency

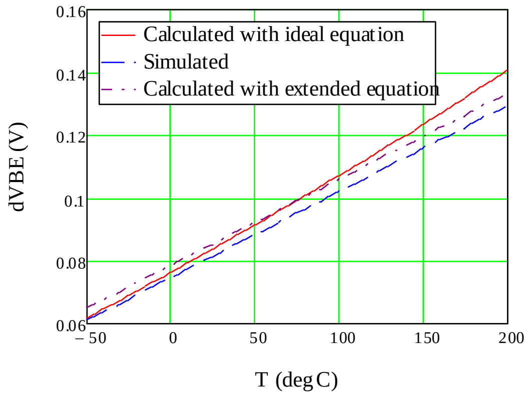


Fig. 6: Comparison of ΔV_{BE} simulated and calculated by equation 7

Further simulations were focused to analyze dependency of ΔV_{BE} based on bipolar transistor size. Three different bipolar transistors were simulated with emitter size of 2x2 µm, 5x5 µm and 10x10 µm under same bias conditions as used for equation (5).

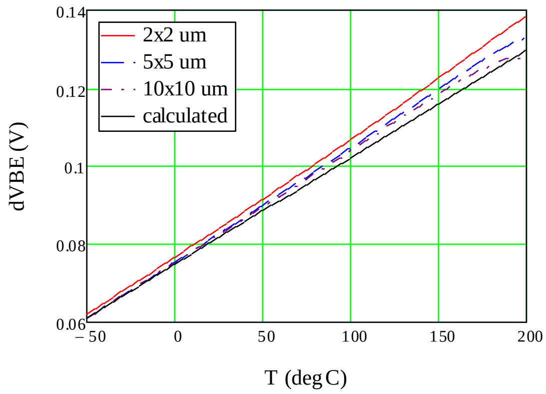


Fig. 7: ΔV_{BE} simulated for different emitter size

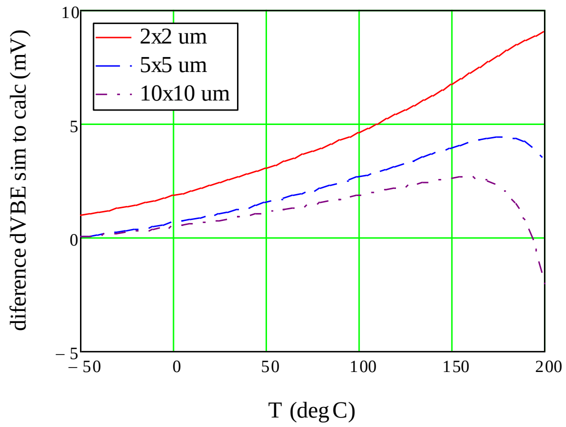


Fig. 8: Difference of ΔV_{BE} simulated for different emitter sizes

Previous figures show that for small junction current densities the leakage plays a role. This is important case for design of low-power voltage reference in automotive industry, where the high junction temperatures are expected.

With this respect the bandgap voltage reference core was simulated. The figure 9 shows simulation results with two the most flat curvature situations from trimming cases. The ideal operational amplifier was used to see what the theoretically reachable temperature curvature is in studied CMOS 180nm technology.

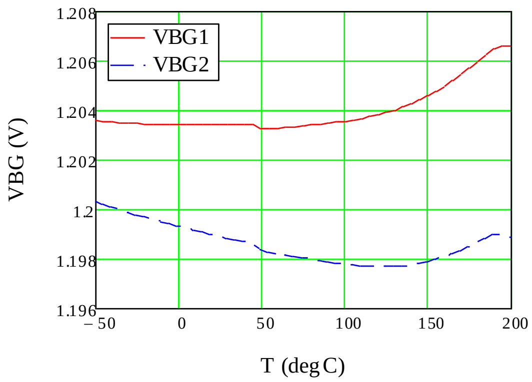


Fig. 9: Final bandgap voltage reference output

Without any additional temperature compensation technique the theoretically reachable case is in between these two curves with spread of 2 mV in temperature range -50 °C to 200 °C which result in 6.7 ppm/°C.

CONCLUSIONS

The CMOS bandgap reference with PNP transistor core was analyzed in this paper. The focus of study was the ΔV_{BE} voltage where is shown that for design calculations of precise voltage reference in wide temperature range is necessary to use more detailed equations taking into account bipolar base and emitter resistances, beta of the bipolar transistor and collector base voltage. The temperature dependency of the emitter resistance needs to be considered as well.
The usage of smaller emitter size bipolar transistors in bandgap voltage reference core is the best choice in case of low power design and high temperatures.

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