ROMANIAN JOURNAL OF INFORMATION SCIENCE AND TECHNOLOGY
Volume **23**, Number 2, 2020, 176–187

New Extraction Method of the Bipolar Transistor Model Parameters Used in Bandgap Voltage References

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Abstract. A new extraction method of the critical model parameters affecting temperature variation of the bandgap type voltage reference is presented. According to the new method, the two model parameters describing the linear and non-linear temperature dependence of the bandgap type voltage references are extracted from the raw data of the reference voltage vs. temperature and not from direct measurements of the bipolar transistor.

Key-words: bipolar transistor; base-emitter voltage; model parameters; bandgap voltage reference; temperature variation; silicon based temperature sensor.

1. Introduction

The bipolar transistor (BT) is a key device in a large variety of electronic circuits and systems. Computer Aided Design (CAD) tools are used in the design phase to simulate the behavior of the corresponding silicon devices. Mathematical models, based on measurements, are created and used in simulations. In most of the DC and/or low frequency applications the BTs are used differentially such that their absolute characteristics are not critical.

However, there are applications like bandgap voltage reference (BVR), where the BT's absolute parameters are critical. Traditionally, the model parameters (MPs) of the BTs affecting the temperature dependence of the BVR and silicon-based temperature sensors (STS) are extracted in the Lab with extreme care for the temperature and instrumentation accuracy. There is a very low probability for the silicon results and simulations of the BVRs and STSs to match. As a result, few iterations are required in order to minimize temperature coefficient (TC), adding extra costs related to the design phase. MPs extraction methods of the BT based on three-temperature points with or without temperature sensors on chip have been published in [1, 2, 3]. All these methods require at least one high accuracy temperature measurement. The proposed method avoids the issues related to the temperature sensitivity. According to the method, the BT that needs to be characterized is part of a precision BVR. From the raw data of real BVR vs. temperature only two measurements are required, corresponding to two temperatures. Based on these measurements two key MPs are extracted: extrapolated bandgap voltage, V_{G0}, and saturation current temperature exponent, denoted as η or, as we prefer, XTI. The proposed method offers to all BVR designers a powerful tool helping them to find the right values for the two key parameters defining the bandgap type voltage (BGV). The efficiency of the new method based on two temperatures was tested on low drop voltage regulators (LDOs) in plastic package with 5V nominal output voltage.

2. Base-emitter voltage temperature dependence

According to [4,5,6], (Fig1), the BT base-emitter voltage (BEV) temperature dependence is:

$$V_{be}(T) = V_{G0} - (V_{G0} - V_{be0})\frac{T}{T_0} - XTI\frac{kT}{q}ln\Big(\frac{T}{T_0}\Big) + \frac{kT}{q}ln\left(\frac{I_c(T_0)(\frac{T}{T_0})^c}{I_c(T_0)}\right) \quad (1)$$

Where: $V_{be}(T)$, the BEV at a current absolute temperature T; V_{G0}, extrapolated to 0K bandgap voltage; V_{be0}, BEV at a reference temperature T_0; kT/q, thermal voltage; $I_c(T)$, collector current at the temperature T; $I_c(T_0)$, collector current at temperature T_0; c, collector current temperature exponent. Assuming that "c" coefficient is known three unknowns are still to be found: V_{G0}, XTI and V_{b0}. The first two terms in (1) correspond to the linear temperature part of the BEV; the last two terms in (1) represent the non-linear temperature part of the BEV.

For temperature independent collector current, c=0, the BEV temperature variation is:

$$V_{be}(T) = V_{G0} - (V_{G0} - V_{be0})\frac{T}{T_0} - XTI\frac{kT}{q}ln\Big(\frac{T}{T_0}\Big) \quad (2)$$

For collector current Proportional to Absolute Temperature (PTAT), c=1, equation (1) becomes:

$$V_{be}(T) = V_{G0} - (V_{G0} - V_{be0})\frac{T}{T_0} - (XTI-1)\frac{kT}{q}ln\Big(\frac{T}{T_0}\Big) \quad (3)$$

For collector current Complementary to Absolute Temperature (CTAT), with c≅–1, slightly nonlinear, the equation (1) is:

$$V_{be}(T) = V_{G0} - (V_{G0} - V_{be0})\frac{T}{T_0} - (XTI+c)\frac{kT}{q}ln\Big(\frac{T}{T_0}\Big) \quad (4)$$

According to (1) to (4), in order to extract the model parameters, $V_{G0},\ V_{be0}$, and XTI, three pairs of temperature-voltage remain to be measured.

The extraction methods of the MPs presented in [1] and [2] are based on direct measurements of the BEV. The solutions for XTI and V_{G0} can be determined starting from equation (2) using three BEV measurements $(V_{be}(T_1), V_{be}(T_0)/V_{be0}, V_{be}(T_2))$ at three different temperatures $(T_1, T_0$ and $T_2)$.

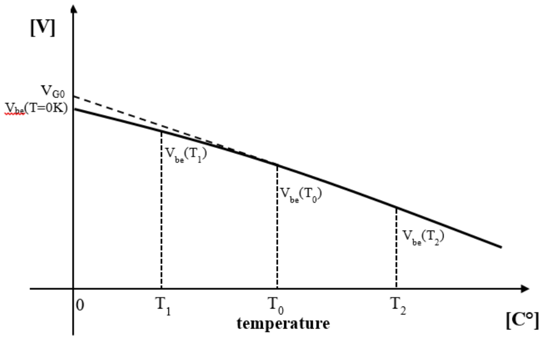

Fig. 1. BEV variation with temperature.

$$V_{be}(T_1) = V_{G0} - (V_{G0} - V_{be0})\frac{T_1}{T_0} - XTI\frac{kT_1}{q}ln\Big(\frac{T_1}{T_0}\Big) \tag{5}$$

$$V_{be}(T_2) = V_{G0} - (V_{G0} - V_{be0})\frac{T_2}{T_0} - XTI\frac{kT_2}{q}ln\Big(\frac{T_2}{T_0}\Big) \tag{6}$$

From (5) and (6) the following two equations can be extracted:

$$T_0V_{be}(T_1) - T_1V_{be}(T_0) = (T_0 - T_1)V_{G0} + XTI\frac{kT_1T_0}{q}ln\frac{T_0}{T_1} \tag{7}$$

$$T_2V_{be}(T_0) - T_0V_{be}(T_2) = (T_2 - T_0)V_{G0} + XTI\frac{kT_2T_0}{q}ln\frac{T_2}{T_0} \tag{8}$$

From (7) and (8) we can extract the MPs of the BT based on the corresponding three temperature-voltage measurements:

$$XTI = \frac{(T_0 - T_1)[T_2V_{be}(T_0) - T_0V_{be}(T_2)] - (T_2 - T_0)[T_0V_{be}(T_1) - T_1V_{be}(T_0)]}{\frac{kT_0}{q}\Big[T_2(T_0 - T_1)ln(\frac{T_2}{T_0}) - T_1(T_2 - T_0)ln\Big(\frac{T_0}{T_1}\Big)\Big]} \tag{9}$$

$$V_{GO} = \frac{[T_2V_{be}(T_0) - T_0V_{be}(T_2)]T_1ln\Big(\frac{T_0}{T_1}\Big) - [T_0V_{be}(T_1) - T_1V_{be}(T_0)]T_2ln\Big(\frac{T_2}{T_0}\Big)}{(T_2 - T_0)T_1ln\Big(\frac{T_0}{T_1}\Big) - (T_0 - T_1)T_2ln\Big(\frac{T_2}{T_0}\Big)} \tag{10}$$

The main source of errors in this method is temperature inaccuracy. According to [2], an error of ΔT_0 in measuring temperature T_0 can lead to errors, for the two key MPs of the BT, as large as:

$$\Delta V_{G0} \simeq \Delta T_0\frac{-2T_1T_2(V_be(T_1) - V_be(T_2))}{(T_0 - T_1)(T_0 - T_2)(T_2 - T_1)} \tag{11}$$

and

$$\Delta XTI \simeq -\Delta V_{G0}\left(\frac{-kT_0}{q}\right)^{-1} \tag{12}$$

According to [2], for three BEVs, 725.27mV, 627.18mV, 526.59mV, at three corresponding temperatures, T = 273K, 323K, and 373K, the values for XTI and V_{G0}, with a ΔT_0 deviation in T_0, was calculated. Considering a ΔT_0 error as small as $\pm 0.1C^\circ$, this causes an error of $\pm$16mV in V_{G0} ($\approx$1.4%) and $\pm$0.6 in XTI ($\approx$16%). The influence of T_1 and T_2 errors is half as large as those due to an error of ΔT_0. The conclusion is that a $\pm 0.1C^\circ$ error in temperature measurements is too large to determine MPs of the BT for high precision requirements. The main disadvantage of the three points method is the need of three high accuracy temperature measurements.

A different way of extracting the MPs, also based on direct measurements of BEV, is presented in [2]. To minimize temperature sensitivity only one temperature is measured directly. The other two are calculated indirectly based on the BEV difference of two BTs operating at different collector current density. For temperature independent collector current the BEV of the device under test (DUT) corresponds to (2). Fig. 2 shows the circuit used to indirectly extract the two temperatures, T1 and T2.

$$T_1 = \frac{\Delta V_{be}(T_1)}{\Delta V_{be}(T_0)} T_0 \tag{13}$$

$$T_2 = \frac{\Delta V_{be}(T_2)}{\Delta V_{be}(T_0)} T_0 \tag{14}$$

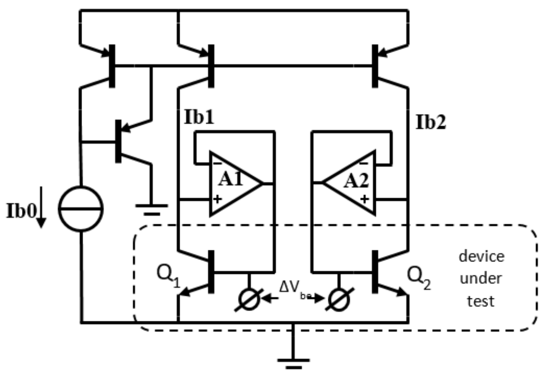

Fig. 2. ΔV_{be} measurement setup, [2].

As a result, only one temperature is independently measured, T_0, while the other two, T_1 and T_2, are calculated. This method does not solve the big errors introduced by the accuracy of the T_0 measurement, only offers a solution to avoid measurements for the other two temperatures. As for the first method, ignoring the errors introduced by T_1 and T2 measurements, a ΔT_0 error as small as $\pm 0.1°$C causes an error of $\pm$16mV in VG0 ($\approx$1.4%) and $\pm$0.6 in XTI ($\approx$16%).

For high precision circuits, the two methods presented might prove too expensive to obtain a very high accuracy of the extracted parameters and even then, it might not be enough. The key advantage of the proposed method is the low temperature sensitivity required to extract MPs with high accuracy.

3. Bandgap type voltage reference

Precision BGV circuits based on stacked delta–V_{be} (ΔV_{be}) cells, (Fig.3), [9 – 14], has been designed and tested. The PTAT voltage part, V_ PTAT, of the BGV, is obtained using a stack of few individual ΔV_{be}, cells, 1 . . . 2 (Fig.4).

A resistorless ΔV_{be} cell, Fig.3, is based on two bipolar transistors, 340 and 350, operating at different collector current densities: 340 as high collector current density and 350 as low collector current density. Two bias current generators, 310 and 320, force the same currents through the collectors of the two bipolar transistors. The difference in their collector current densities is set by the corresponding number of emitters, one emitter for 340 and n emitters for 350. An NMOS transistor, 360, and the bipolar transistor 350 act as a nested amplifier, generating at the output node “C” the corresponding output voltage. At ambient temperature, each cell generates a typical PTAT voltage of 50mV to 100mV, depending on the collector current density ratio of the bipolar transistors in the cell. The output voltage of the stack, V_{PTAT}, (see Fig.4) is proportional to absolute temperature (PTAT) and very consistent against process variations. Its value at ambient temperature depends on the number of the cells in the stack.

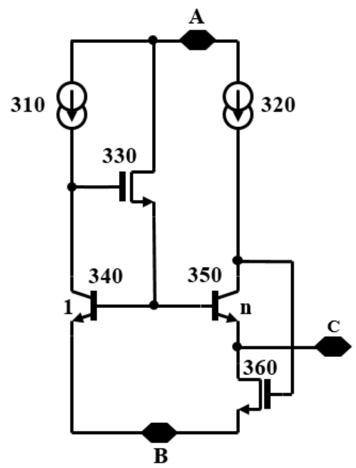

Fig. 3. Base-emitter voltage difference cell.

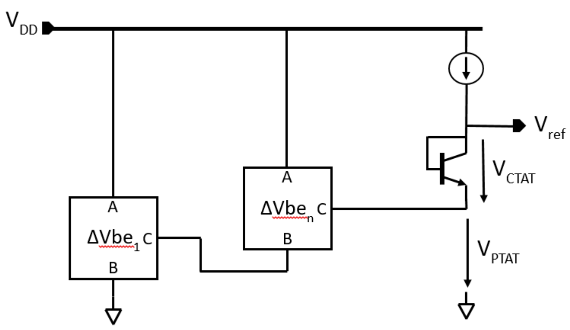

Fig. 4. Precision BGV circuit based on stacked delta-V_{be} cells.

4. The extraction method

The new extraction method presents a way to extract the MPs of BT, not from the BEV measurements but, instead, from manufactured bandgap voltage reference or LDOs. According to [6] when PTAT and CTAT voltage components are well balanced around a middle temperature point (T_0), the compound voltage (which is BGV) is expressed based on only two unknowns, V_{G0} and XTI. A first order compensated BVR is based on the summation of two voltage components with opposite temperature variations. The first voltage component corresponds to the BT's BEV, which is CTAT. The second voltage component is PTAT (16), representing a gained replica of the ΔV_{be} (15) of two BTs operating at different collector current densities.

$$\Delta V_{be} = \frac{kT}{q} ln(n) \tag{15}$$

$$V_{PTAT} = G_p \Delta V_{be} \tag{16}$$

$$V_{CTAT} = V_{be}(T) \tag{17}$$

From (1), (15), (16), (17) the bandgap voltage reference is determined as:

$$V_{ref} = V_{G0} - (V_{G0} - V_{be0})\frac{T}{T_0} - XTI\frac{kT}{q}ln\left(\frac{T}{T_0}\right) + \frac{kT}{q}ln\left[\frac{I_C(T)}{I_C(T_0)}\right] + G_p\frac{kT}{q}ln(n) \tag{18}$$

The BGV can be set as temperature insensitive at a temperature T_0. From here, after straightforward calculations and considering I_C constant over temperature, G_p can be determined.

$$\left.\frac{\partial V_{ref}}{\partial T}\right|_{T_0} = 0 \rightarrow G_p = \frac{V_{G0} - V_{be0} + XTI\frac{kT}{q}}{\frac{kT}{q}ln(n)} \tag{19}$$

Replacing G_p in (18), a new expression for V_{ref} can be determined with V_{G0} and XTI being the only unknowns. The two voltage components are balanced (CTAT and PTAT) so the compound voltage (V_{ref}), [6], is temperature dependent according to (20):

$$V_{ref} = V_{G0} + XTI\frac{kT}{q}\left[1 - ln\frac{kT}{q}\right] \tag{20}$$

According to (20), the temperature variation of the reference voltage displays a "bow" type nonlinearity. Fig.5 shows this nonlinearity for a BVR based on BTs having V_{G0}=1.16V and XTI=3.8. For the minimum temperature coefficient (TC) the reference voltage has the same value at the two extreme temperatures, T_1= -40°C and T_2=150°C as, Fig.5 shows.

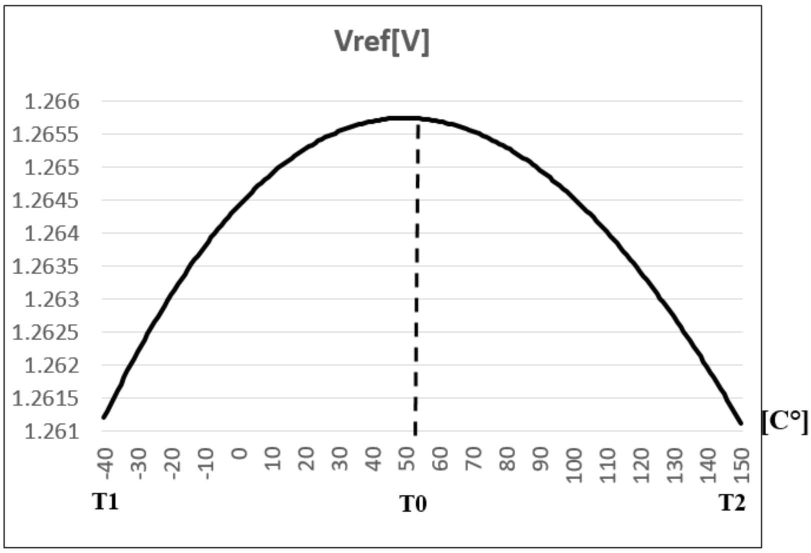

Fig. 5. First order compensated BVR .

At the middle of the temperature range, T_0, the reference voltage, $V_{ref}(T_0)$, has zero TC, with a value:

$$V_{ref}(T_0) = V_{G0} + XTI\frac{kT_0}{q} \tag{21}$$

The reference voltage difference corresponding to the two temperatures, T_0 and T_1 is:

$$V_{ref-c} = V_{ref}(T_0) - V_{ref}(T_1) \tag{22}$$

or

$$\Delta V_{ref-c} = XTI\frac{kT_0}{q}\left[1 - \frac{T_1}{T_0}\left(1 - ln\frac{T_1}{T_0}\right)\right] \tag{23}$$

The XTI parameter results from (23) as:

$$XTI = \frac{\Delta V_{ref-c}}{\frac{kT_0}{q}\left[1 - \frac{T_1}{T_0}\left(1 - ln\frac{T_1}{T_0}\right)\right]} \tag{24}$$

Then V_{G0} is:

$$V_{G0} = V_{ref}(T_0) - XTI\frac{kT_0}{q} \tag{25}$$

The measured voltage reference is usually unbalanced exhibiting different slopes as Fig.6 shows. In order to apply the method, as presented, the voltages 1 and 2 must be balanced.

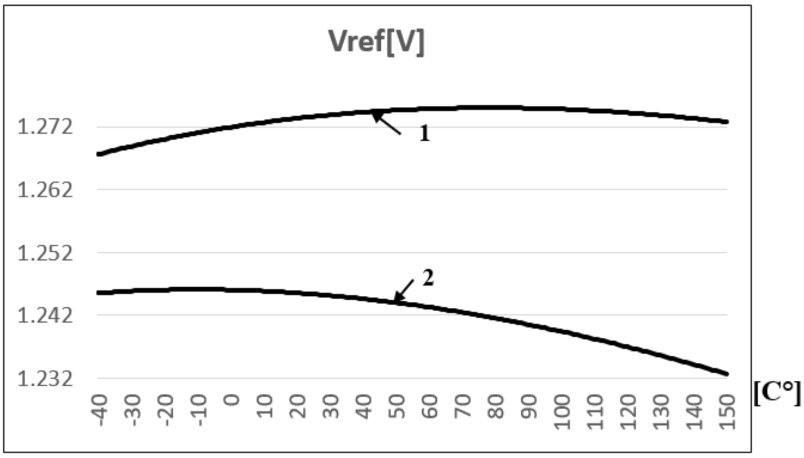

Fig. 6. Un-balanced voltage references vs. temperature.

This is possible if a correction voltage, V_{corr}, is subtracted from the initial voltage reference:

$$V_{corr} = S * T \tag{26}$$

In (26), "S" is the initial BVR slope:

$$S = \frac{V(T_2) - V(T_1)}{T_2 - T_1} \tag{27}$$

Two reference voltage plots, unbalanced – 3 – and balanced – 4 –, are presented in Fig. 7. The main advantage of the new method, unlike the first two presented, is that it completely removes the necessity for high precision temperature measurements.

Considering a balanced BGV, the impact of a ΔT_0 error (29) can be calculated based on (28).

$$V_{ref}(T_0 + \Delta T_0) = V_{G0} + XTI\frac{k(T_0 + \Delta T_0)}{q}\left[1 - ln\frac{\Delta T_0}{T_0}\right] \tag{28}$$

$$\Delta V_{ref}(T_0) = -XTI\frac{kT_0}{q}\left(\frac{\Delta T_0}{T_0}\right)^2 \tag{29}$$

Using (29) and considering XTI = 3.8, T0 = 55°C with kT_0/q=28.27mV, an error ΔT_0 = +0.1°C will result in an $\Delta V_{ref}(T_0)$ error of about -20nV (impossible to measure). This translates further into an error of around 0.17mV in V_{G0}($\approx$ 0.15%) and approximately 0.01 in XTI($\approx$0.25.%). Compared to previous methods, the errors resulted in the MPs of the BT are smaller with more than one order of magnitude.

The presented method provides a way to easily extract XTI and VG0 without the requirement of high precision temperature measurements and, at the same time, with better accuracy than the existing methods.

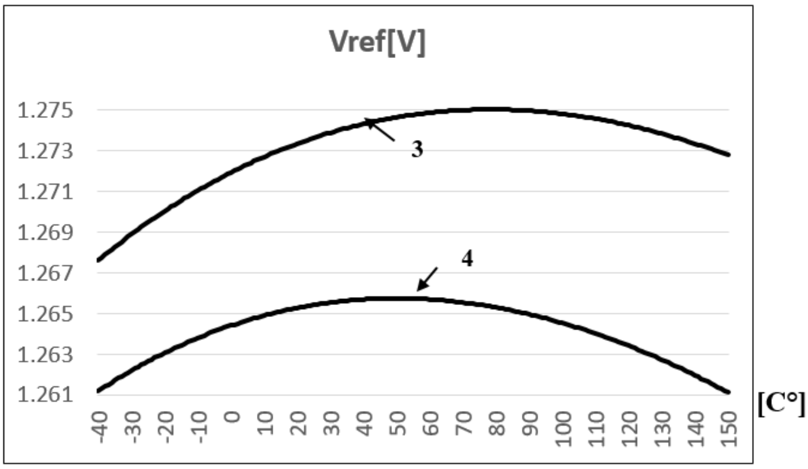

Fig. 7. Un-balanced (3) and balanced (4) voltage references vs. temperature.

5. Silicon results

MP of the BT, XTI and V_{G0}, can also be extracted from different voltage values, other than the BGV. For example, MPs can be extracted from measuring the output voltage of an LDO (Fig.8), by dividing the output voltage with nominal gain factor, $G = 1 + R_f/R_-$.

$$V_{BG} = \frac{V_Q}{1 + \frac{R_f}{R_-}} \pm V_{off} \tag{30}$$

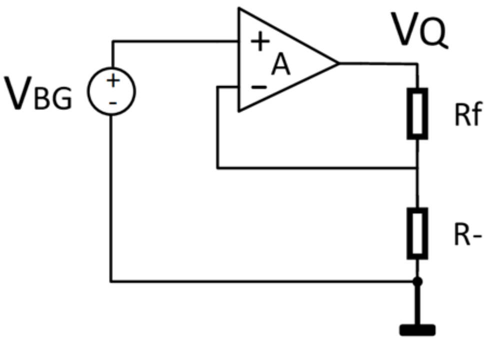

Fig. 8. LDO concept schematic.

By dividing the output voltage of the LDO with nominal gain factor, G, the corresponding bandgap voltage is obtained. Extra errors can occur due to the deviation of feedback resistor ratios and different impedances seen at amplifier inputs. Fig.9 and Fig.10 present the results for 16 silicon production LDO samples where MPs of the BT were extracted using the proposed method.

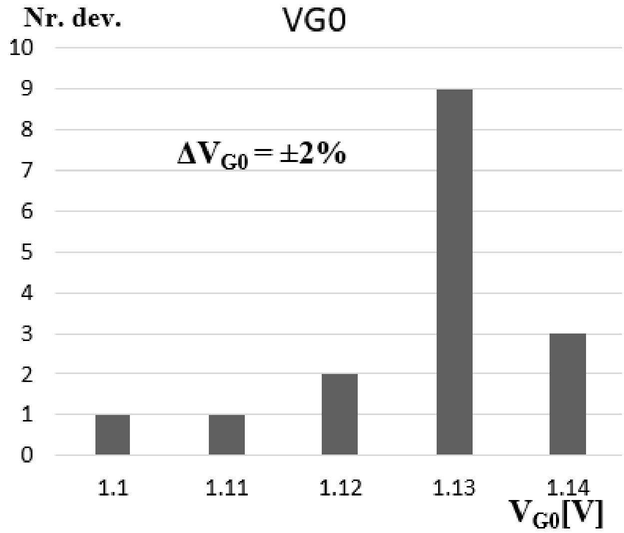

Fig. 9. V_{GO} distribution for 16 devices.

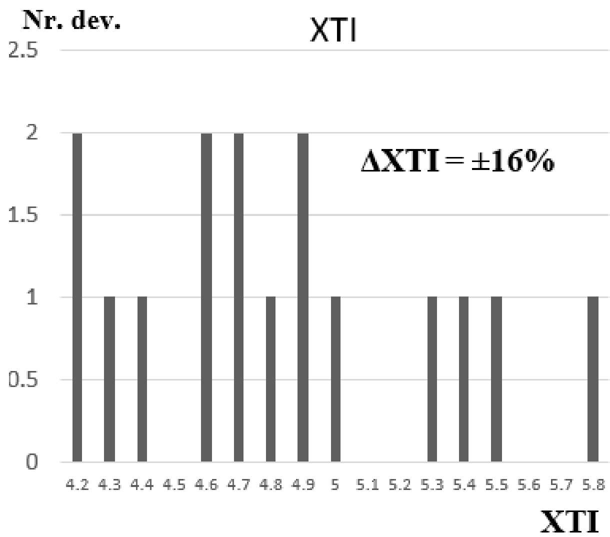

Fig. 10. XTI distribution for 16 devices.

The deviation of the calculated ΔV_{GO} and ΔXTI are due, not only to the applied method, but also to the errors like the offset voltage of the amplifier and gain spread. For the results presented above, the temperature range used for extracting the parameters was narrowed (T1 = 0°C, T2 = 100°C) in order to reduce the influence of the leakage currents. For minimum errors, a precision bandgap type voltage reference based on stacked base-emitter voltage difference cells is recommended like the one published in [9].

6. Errors

The extraction method accuracy can be affected by several factors due to the fact that the method is based on voltage differences. This is more important for XTI MP where the voltage difference is in the range of millivolts. A more detailed error analysis will be the objective of another paper.

6.1. PTAT voltage nonlinearity

Until now it was assumed that the PTAT voltage component of the BGV is perfectly linear and the compound's nonlinearity is strictly related to the base-emitter voltage. The PTAT voltage linearity is affected by the Early effects, reverse and direct, corresponding to the base width modulation. The direct Early effect can be compensated by keeping the collector-base voltages of the two bipolar transistors generating the BEV difference close to zero. The nonlinearity of the PTAT voltage is mainly affected by the reverse Early voltage effect [12], which is in the form of Tlog(T), similar but opposite to the nonlinearity of the BEV.

6.2. Collector current temperature variation

As (4), (5) and (6) show, the collector current temperature variation is critical for the method accuracy. The first recommendation is not to use curvature correction in MPs extraction. From the sensitivity point of view, it is recommended to use CTAT collector currents but in this situation extra nonlinearities will be introduced, which are no more of the Tlog(T) form. Real BGV circuits are based on PTAT collector currents due to their minimum "curvature" type errors. The recommended collector currents to be used for the purpose of MPs extraction, according to the proposed method, are temperature independent. The resistors TCs used to generate collector currents are also important and must be taken into consideration.

6.3. Bandgap voltage narrowingn

It was assumed that the extrapolated bandgap voltage value, V_{G0}, is temperature independent. In reality, [5], due to the bandgap narrowing effect related to the emitter high doping profile, V_{G0} is temperature dependent. For modern technologies a decrease of about 45mV of the bandgap energy has been reported. The temperature dependence of the bandgap narrowing effect can introduce errors around 0.3mV for a temperature range from -40°C to 150°C.

7. Conclusions

A new extraction method for the BT MPs is presented. The proposed method has important advantages over the known methods:

- It is less affected by the temperature stability as the BGV is already compensated for the first order TC;
- It is the first method based on two temperature measurements, even though the nonlinearities require three temperature points.

- Compared to existing methods, the errors of the extracted MPs for BT are smaller with more than one order of magnitude.
- The MPs can be extracted from a dedicated BGV circuit or from any other BGV circuit. If the reference voltage is gained-up by means of amplification the measured data must be accordingly reduced to the unbuffered bandgap voltage reference value;
- The method offers a powerful tool to the analog voltage references designers such that based on the proposed method the designers can easily calibrate their designs after the first silicon.

References

[1] W. RAHAJANDRAIBE *et al. Bandgap Voltage Optimization from On-Chip EG, XTI Value Extraction*, Analog Integrated Circuits Signal Processing, **33**, 85–94, Kluwer Academic Publishers, Netherlands, 2002.

[2] G. MEIJER ang K.VINGERLING, *Measurements of the Temperature Dependence of the* $I_C(V_{be})$ *Characteristics of Integrated Bipolar Transistors*, IEEE J. of Solid-State Circuits, **SC-15**(2), 1980.

[3] Y. TSIVIDIS, *Accuracy Analysis of Temperature Effect in Ic-Vbe Characteristics with application to Bandgap Reference Source*, IEEE J. of Solid_state Circuits, **15**(6), pp. 1076–1084, December 1980.

[4] R. WIDLAR, *An exact expression for the thermal variation of the emitter-base voltage of bi-polar transistors*.

[5] R. WIDLAR, *New Developments in IC Voltage Regulators*, IEEE J.of Solid-State Circuits , **23**(SC-6), pp. 2–7, February 1973.

[6] D. JOHNS and K. MARTIN, *Analog Intefrated Circuit Design*, John Wiley & Sons, INC., New York, 1997.

[7] K. KUJIK, *A Precision Reference Voltage Source*, IEEE J. of Solid-State Circuits, **SC-8**, pp. 222–226, June 1973.

[8] P. BROKAW, *A simple Three-Terminal IC Bandgap Reference*, IEEE J. of Solid-State Circuits, **SC-9**, pp. 388–393, December 1974.

[9] S. MARINCA, US Patents no. 8531169/2015 and 9218015/2015, *Method and circuit for low power voltage reference and bias current generator*.

[10] S. MARINCA, US Patents no. 8531169/2015 and 9218015/2015, *Method and circuit for low power voltage reference and bias current generator*.

[11] A. KALB US Patent no. 9285820/2016, *Ultr-low noise voltage reference circuit*

[12] S. MARINCA, G. BANARIE, V. BUCUR, M. BODEA *A* $\pm 2m^{\circ}C$ *linearity silicon temperature sensor*, International Symposium on Signals, Circuits and Systems (ISSCS), Iasi, Romania, 2017.

[13] S. MARINCA, US Patent no. 9285820/2016, *Circuit and method for compensation for Early voltage effects*.

[14] S. MARINCA, US Patent no. 9658637/2017, *Low power PTAT current and voltage generator*.