# EXPERIMENTAL 0.1 PPM/°C IN A LOW-VOLTAGE CURVATURE-CORRECTED BANDGAP TYPE CIRCUIT.

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**Abstract**: An accurate design method of a low-voltage curvature-corrected bandgap type circuit was previosly reported in DCIS2000, that achieved a theoretical temperature coefficient of less than 0.1 ppm/°C. This result improved almost three times the best theoretical temperature coefficient previously reported. In this paper an experimental temperature coefficient of 0.1 ppm/°C has been obtained in a bandgap type circuit based on the linear sum of two base-emitter voltages.

## I. INTRODUCTION

An accurate design method of a low-voltage curvature-corrected bandgap type circuit was previously reported [1], that achieved a theoretical temperature coefficient of less than 0.1 ppm/°C. This result improved almost three times the best theoretical temperature coefficient previously reported [2].

In this paper an experimental temperature coefficient of 0.1 ppm/°C has been obtained in a bandgap type circuit based on the linear sum of two base-emitter voltages using a design method previously reported [1].

The design method of bandgap references is based on the accurate modeling of the base-emitter voltage.

The approximate expression of the base emitter voltage has been previously used [3],

$$\mathbf{V_{BE}(T) = \left\{ V_{G0} - (h - m)\frac{kT_r}{q} \right\} - l\,T + (h - m)\frac{k}{q}\left(T - T_r - T \ln \frac{T}{T_r}\right)} \qquad \mathbf{(1)}$$

This expression considers the linear approximation of the bandgap voltage $V_G(T)$ [4],

$$\mathbf{V_G = V_{G0} - aT} \qquad \mathbf{(2)}$$

where,

$$\mathbf{a = dV_G / dT\big|_{T=T_r}}$$

$$\mathbf{l = \frac{V_{G0} + \frac{kT}{q}(h - m) - V_{BE}(T_r)}{T_r}}$$

$T_r$: reference temperature in Kelvin

$V_{GO}$: bandgap voltage extrapolated to zero Kelvin

**h**: parameter related to the temperature dependence of the mobility of minority carriers in the base region

This approximation has been recently abandoned in favor of an accurate non linear expression of $V_G(T)$ seeking an improvement of the temperature coefficient in bandgap type references. However it was shown by these authors [1] that the linear approximation of $V_G(T)$ can still achieve very accurate design of bandgap references and can take into account also the base impurity concentration that causes the variation of $V_{G0}$ and the correlation between **h** and $\mathbf{V_{GO}}$ [5].

The design method will be reviewed briefly.

## II. DESIGN METHOD [1].

The bandgap type circuit based on the linear sum of two base-emitter voltages biased with a constant current $I_{CONST}$ and a PTAT current $I_{PTAT}$ is shown in Fig.1.

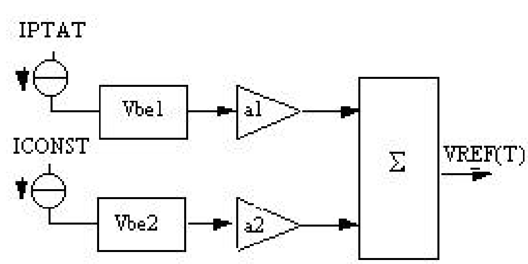



**Fig.1 Block diagram of the curvature-corrected bandgap type circuit**

The output reference voltage is given by [1],

$$\hat{V}_{REF}(T) = a_1 \hat{V}_{BE1}(T) + a_2 \hat{V}_{BE2}(T) \qquad (4)$$

where,

$$\hat{V}_{BE1}(T) = \hat{V}_{G0}\left(1 - \frac{T}{T_r}\right) - \frac{T}{T_r} V_{BE1}(T_r) + (\hbar - 1)\frac{k}{q}\left(T \ln \frac{T}{T_r}\right) \qquad (5)$$

$$\hat{V}_{BE2}(T) = \hat{V}_{G0}\left(1 - \frac{T}{T_r}\right) - \frac{T}{T_r} V_{BE2}(T_r) + \hbar \frac{k}{q}\left(T \ln \frac{T}{T_r}\right) \qquad (6)$$

and, $\hbar$ and $\hat{V}_{G0}$: fitting values obtained from measurements of $V_{BE2}(T)$ at three temperatures of the operating range: $T_{min}$, $T_r$, $T_{max}$.

From equations 4, 5 and 6 it can be shown that the nonlinear dependence with temperature of $\hat{V}_{REF}(T)$ can be cancelled if,

$$\frac{a_1}{a_2} = \frac{\hbar - m_2}{\hbar - m_1} \qquad (7)$$

It can also be shown that linear dependence can be cancelled if,

$$a_1 \hat{l}_1 = -a_2 \hat{l}_2 \qquad (8)$$

Solving the system of equations 4, 7 and 8 the design parameters $a_1$, $a_2$ and $V_{BE1}(T_r)$ can be obtained.
A mathematical data processing program was developed to find $\hbar$, $\hat{V}_{G0}$ and the design parameters $a_1$, $a_2$ and $V_{BE1}(T_r)$.

## III. MEASUREMENT SET-UP

The measurement set-up shown in Fig.2 allowed to obtain parameters $\hbar$ and $\hat{V}_{G0}$ from temperature measurements and to assess $V_{REF}(T)$ in the 20-100°C temperature range.
A sensitivity analysis was performed to set the accuracy requirements of all variables to measure such a low temperature coefficient :

a) Temperature: Resolution better than 0.01 °C in the temperature range
b) Voltage: Resolution of 1 μV in the 1 volt scale
c) Current: Current stability should not produce a change greater than 0.2 μV in $V_{BE1}(T)$ and $V_{BE2}(T)$.

A Pt-1000 DIN IEC 751 with a temperature coefficient of 0.00385/K was inserted together with the device under test (DUT) in a copper block inside a liquid bath thermostat to achieve a temperature stability of 1 mK.

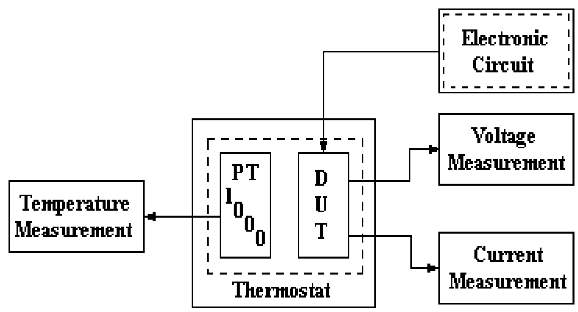



**Fig. 2 Block diagram of the measurement setup**

Base-emitter voltage measurements were performed with a Keithley 2182 nanovoltmeter with 0.1 μV resolution in the 1 V scale. Measurements were taken after temperature variations were smaller than 1 mK as shown by the Pt-1000 RTD reading.

## IV. EXPERIMENTAL RESULTS

The experiments were performed with two types of devices, matched monolithic dual NPN bipolar transistor MAT01 and substrate PNP transistor in 0.5 μm CMOS technology [6].

In both types of devices, parameters $\hbar$, $\hat{V}_{G0}$, $a_1$, $a_2$ and $V_{BE1}(T_r)$ were calculated using a mathematical data processing program whose screen is shown in Fig.3.

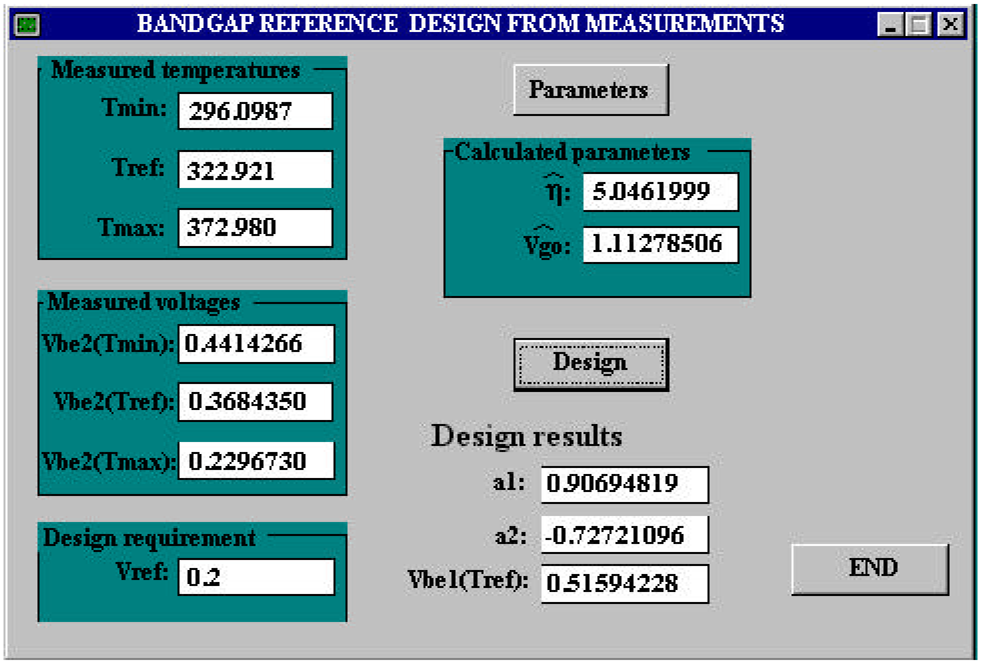
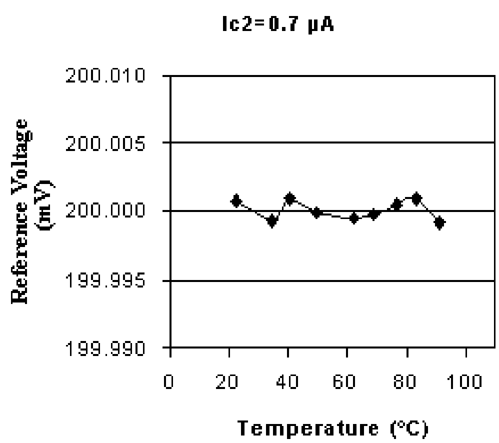



**Fig.3 Program screen with design results for MAT01#1.**

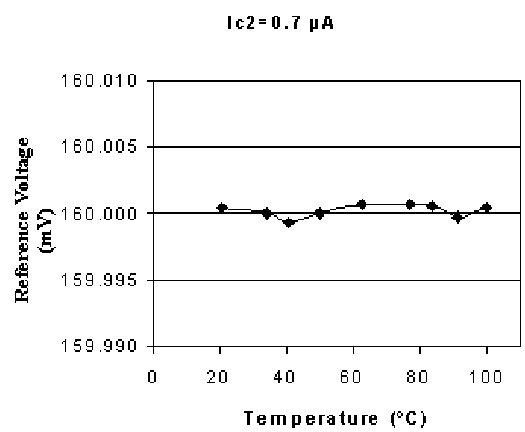
$V_{REF}(T)$ was obtained from expression 4 by measuring $V_{BE1}(T)$ and $V_{BE2}(T)$ at 10°C intervals; $I_{CONST}$ was held at 0.7 µA and $I_{PTAT}$ was varied linearly with absolute temperature.

The results of $V_{REF}(T)$ for both types of devices are shown in Fig.4 and Fig.5 respectively.




**CT=0. 121 ppm/°C**

**Fig. 4 Variation of $V_{REF}(T)$ with temperature for device MAT01 #1**




**CT=0.1016 ppm/°C**

**Fig.5 Variation of $V_{REF}(T)$ with temperature for CMOS substrate PNP # N1202**

These measurements were also performed at other values of constant bias current and in all cases the temperature coefficient was smaller than 0.2 ppm/°C in the 20-100°C temperature range.

## CONCLUSIONS

A 0.1 ppm/°C temperature coefficient was achieved experimentally in a bandgap type circuit, similar to theoretical results previously reported by the authors in DCIS2000 [1].

Two types of devices were used, dual bipolar NPN transistors MAT-01 and CMOS substrate PNP transistors with similar results of the temperature coefficient

The design method of the bandgap type circuit considers the effect of base impurity concentration through parameters $\hat{\eta}$ y $\hat{V}_{G0}$ .

Such low temperature coefficient has not been previously reported. These results can be useful in the design of IC bandgap voltage references.

## REFERENCES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