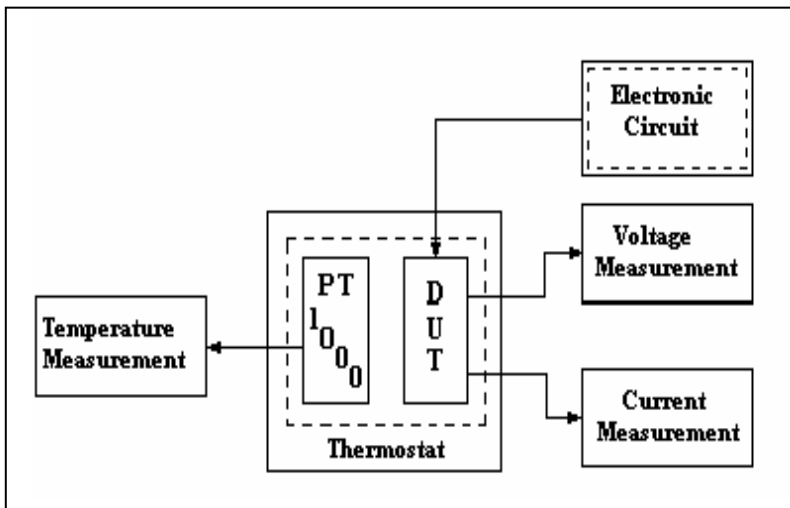


# PHYSICAL DESIGN TO VERIFY THEORETICAL 0.1 PPM/°C STABILITY IN A BANDGAP TYPE CIRCUIT



## ABSTRACT

The propose of this paper is the experimental validation of a temperature coefficient less than 0.2 ppm/°C, theoretically obtained in a low-voltage bandgap references type circuit, using a design method based on the linear sum of two base-emitter voltages.

The experiment consists of obtaining  $V_{REF}(T)$  from experimental measurements of base-emitter voltage in a 20 to to 100 °C interval.

The measurements of  $V_{BE}(T)$  were performed on MAT01 industrial bipolar transistors.

**Dra. Alicia Polanco:**  
**Investigadora Auxiliar,**  
Centro de Investigaciones  
en Microelectrónica,  
CIME/ISPJAE Cuba

**Dra. Agnes Nagy:**  
**Profesora Auxiliar,**  
Centro de Investigaciones  
en Microelectrónica,  
CIME/ISPJAE Cuba

**Dr. Manel Alvarez:**  
**Profesor Titular,**  
Facultad de Inganieria  
Industrial/ISPJAE Cuba

Grupo de Sensores  
Térmicos,  
[alicia.polanco@electronica.cujae.edu.cu](mailto:alicia.polanco@electronica.cujae.edu.cu)

## KEY WORDS

Physical design, temperature coefficient, bandgap voltage references

## 1. INTRODUCTION

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

This design method uses the approximate expression of the base emitter voltage [3],

$$V_{BE}(T) = \left\{ V_{G0} - (\eta - m) \frac{kT_r}{q} \right\} - \lambda T + (\eta - m) \frac{k}{q} (T - T_r - T \ln \frac{T}{T_r}) \quad (1)$$

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

$$V_G = V_{G0} - \alpha T \quad (2)$$

where,

$$\alpha = dV_G / dT|_{T=T_r}$$

$$\lambda = \frac{V_{G0} + \frac{kT_r}{q} (\eta - m) - V_{BE}(T_r)}{T_r} \quad (3)$$

$T_r$ : reference temperature in Kelvin

$V_{G0}$ : bandgap voltage extrapolated to zero Kelvin

$\eta$ : parameter related to the temperature dependence of the mobility of minority carriers in the base region

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  $\eta$  and  $V_{G0}$  [5].

The design method will be reviewed briefly.

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.

The output reference voltage is given by [1],

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

where,

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

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

and,  $\hat{\eta}$  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 of  $\hat{V}_{REF}(T)$  with temperature can be cancelled if,

$$\frac{a_1}{a_2} = \frac{\hat{\eta} - m_2}{\hat{\eta} - m_1} \quad (7)$$

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

$$a_1 \hat{\lambda}_1 = -a_2 \hat{\lambda}_2 \quad (8)$$

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  $\hat{\eta}$ ,  $\hat{V}_{G0}$  and the design parameters  $a_1$ ,  $a_2$  and  $V_{BE1}(T_r)$ .

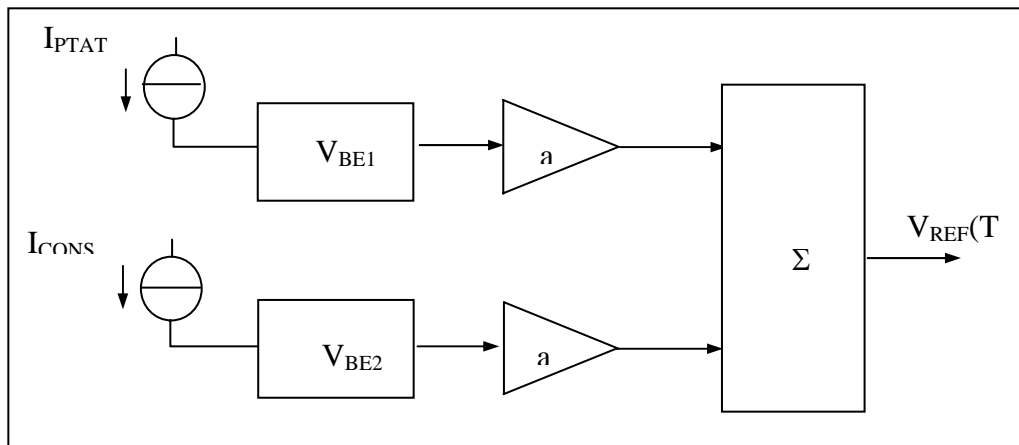


Figure1. Block diagram of the curvature-corrected bandgap type circuit

## 2. REQUIREMENTS

To achieve a processing data error less than 0.25 ppm/°C in the 20 to 100 °C interval, a sensitivity analysis was performed to establish measurement requirements of temperature, voltage and current, with the following results:

- Temperature: Resolution better than 0.01 °C.
- Base-emitter voltage: Resolution better than 1  $\mu\text{V}$
- Current: Time stability of current  $I_{C1}$  and  $I_{C2}$  should warrant a stability of the base-emitter voltages better than 0.2  $\mu\text{V}$ .

To fulfill these requirements a measurement setup was prepared for the devices under test (DUT). The measurement block diagram is shown in Fig.2.

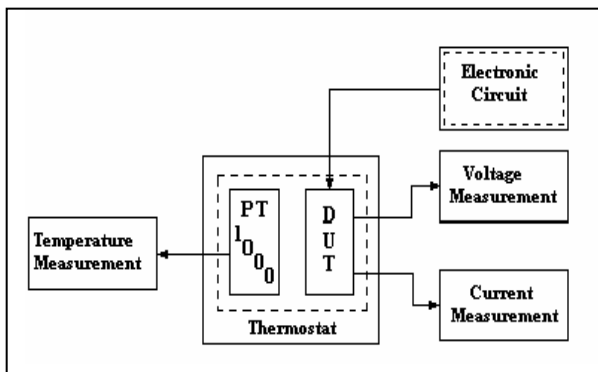


Figure 2. Block diagram of measurement setup.

A large copper block was placed within a liquid thermostat of 0.1°C stability. The RTD sensor and the DUT were inserted into the copper block, that allowed to reach a stability better than 1 mK.

A standard platinum resistor PT1000 DIN EN60751 [6] was used as temperature sensor. The resistance of the PT1000 was measured with a Keithley digital electrometer model 614.

Base-emitter voltages  $V_{BE1}(T)$  and  $V_{BE2}(T)$  were measured with the Keithley nanovoltmeter model 2182 [7] with 100 nV resolution in a 1 V scale.

Base-emitter voltage measurements at each temperature were performed only after the reading of the nanovoltmeter did not change more than  $\pm 0.1 \mu\text{V}$  which is equivalent to a temperature stability of 50  $\mu\text{K}$  approximately (taking into account the variation of  $V_{BE} \cong -2 \text{ mV}/^\circ\text{C}$ ). After every 10 °C temperature change, a minimum of 3 hours were required to achieve that stability.

During the whole measurement process the thermostat was kept on. Measurements with these electronic equipment were performed 3 hours after being turned on.

The assessment circuit for the bipolar reference is shown in Fig. 3. The device under test is the pair  $Q_1, Q_2$ . Collector bias currents are determined by  $R_1, P_1, R_2, P_2$ . Operational amplifiers 084 cancel forward Early effect, and the influence of base

currents. Collector-ground capacitors were connected to eliminate parasitic oscillations.

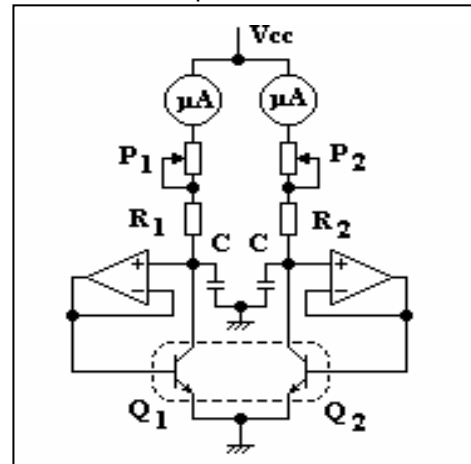


Figure 3. Measurement diagram of  $V_{BE}$

The average temperature coefficient can be obtained from,

$$TC = \frac{V_{REFhigh} - V_{REFlow}}{V_{REF}(T_r)\Delta T} \quad (9)$$

where,  $V_{REFhigh}$  and  $V_{REFlow}$  are the maximum and minimum values of the reference voltage in the temperature interval.

## 3. MEASUREMENT IN MAT01 BIPOLAR TRANSISTOR

Considering the values  $I_{C2}=0.7 \mu\text{A}$  of  $Q_2$  transistor,  $m_1=0, m_2=1, V_{REF}=0.2 \text{ V}$ , and measuring  $V_{BE2}$  at three temperatures  $T_{inf}, T_{sup}$  and  $T_r$ , the design parameters  $\eta, \bar{V}_{G0}, a_1, a_2$  and  $V_{BE1}(T_r)$ , were calculated using the mathematical program whose screen shot with the obtained values is shown in Fig. 4.

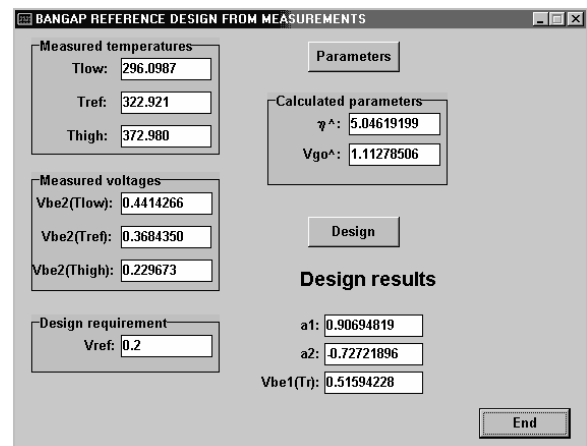


Figure 4. Screen shot of the program with results for MAT01

$Q_1$  was biased at  $T_r$  to set the value  $V_{BE1}(T_r)$ .  $I_{C1}$  at other temperatures was calculated as a PTAT

current to bias  $Q_1$ .  $V_{REF}(T)$  was calculated using the measured values of  $V_{BE1}(T)$  and  $V_{BE2}(T)$  in expression (4).

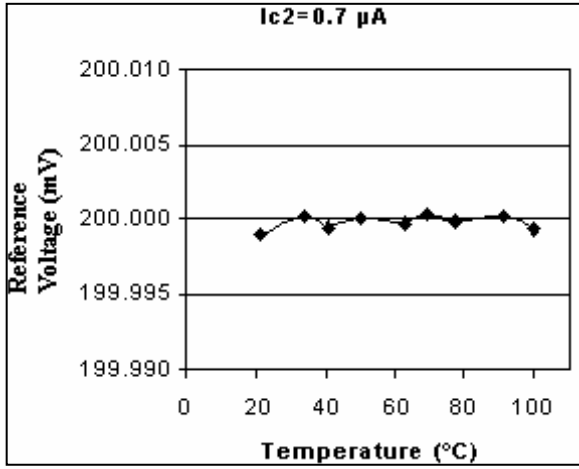


Figure 5. Variation of  $V_{REF}(T)$  with temperature using MAT01

Results of  $V_{REF}(T)$  are shown in Fig. 5., where an average temperature coefficient of 0.092 ppm/°C was obtained [8].

### 5. REDUCING CURRENT RATIO $I_{C2}/I_{C1}$ THROUGH PARAMETER $m$

To improve the relative tolerance of the current ratio  $I_{C2}/I_{C1}$  it is convenient to reduce it [9].

Considering PTAT collector current expression,

$$I_C(T) = I_C(T_r) \left( \frac{T}{T_r} \right)^m \quad (10)$$

where  $m$  determines temperature dependence of collector current and using the expression (11) for transistors  $Q_1$  and  $Q_2$  of Fig. 3,

$$I_C(T) = I_S(T) \exp\left(\frac{qV_{BE}(T)}{kT} - 1\right) \quad (11)$$

the following expression can be obtained,

$$\frac{I_{C2}}{I_{C1}} = \exp\left(\frac{V_{BE1}(T_r) - V_{BE2}(T_r)}{\frac{k}{q}T_r}\right) \quad (12)$$

From expression (12) it is possible to reduce  $I_{C2}/I_{C1}$  decreasing the difference of base-emitter voltages of  $Q_1$  and  $Q_2$ . From Fig. 3 with constant  $I_{C2}$ , i.e.,  $m_2=0$  and from expression (7) and (8) the following expression can be obtained,

$$m = \frac{\eta[V_{BE1}(T_r) - V_{BE2}(T_r)]}{\bar{V}_{G0} - V_{BE2}(T_r)} \quad (13)$$

From expression (4) and (12) it can be seen that a lower value of  $m$  will give a design solution with a lower difference of base-emitter voltages and therefore with a lower current ratio  $I_{C2}/I_{C1}$ .

A new version of the design mathematical program allowed to give  $m_1$  and  $m_2$  as input data.

The design with  $m_1=0.5$ ,  $m_2=0$  and  $V_{REF}=100$  mV was performed again.

A screen shot of the new program is shown in Fig. 6; notice that the maximum possible value of  $V_{REF}$  that is a solution, is also shown. It can also be seen that  $V_{BE1}(T_r) - V_{BE2}(T_r)$  is smaller.

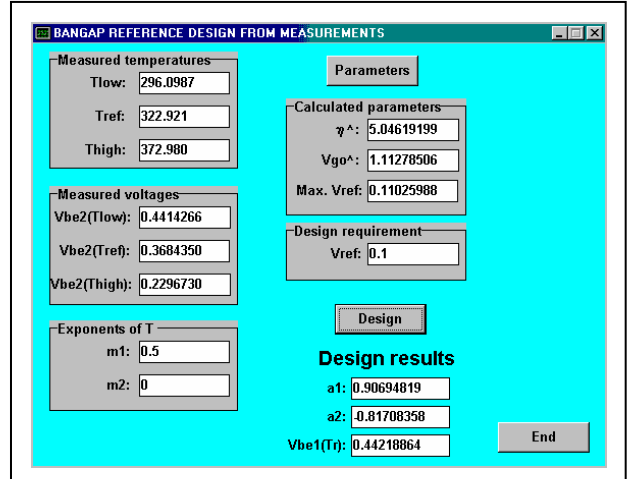


Figure 6. Screen shot of the program that allowed to design with  $m_1$  and  $m_2$  in MAT01

Experimental measurements performed in this case allowed to obtain  $V_{REF}(T)$  as shown in Fig.7, with an average temperature coefficient of 0.133 ppm/°C

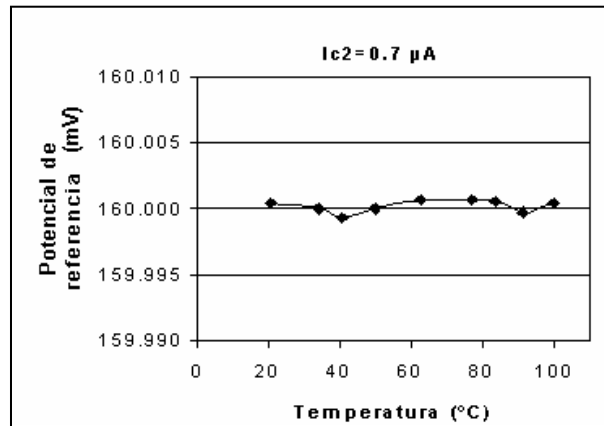


Figure 7 Variation of  $V_{REF}(T)$  with temperature using  $m_1=0.5$ .

### 6. CONCLUSIONS

A physical design to verify the temperature coefficient of a bandgap type circuit was realized and a measurement setup to measure base-emitter voltages as a function of temperature was established with a resolution better than 0.1  $\mu$ V and a temperature stability better than 1 mK.

It was verified experimentally that the average temperature coefficient in the temperature range of 20 – 100 °C of  $V_{REF}$  was approximately 0.1 ppm/°C, similar to theoretical results previously reported in DCIS2000 [1]. Such a low temperature coefficient

has not been previously published in literature for a bandgap reference type circuit.

A new design procedure to reduce the ratio of bias currents in transistors using as a parameter the exponent  $m$  of temperature was developed and verified. This method has not been reported previously.

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## AUTHORS



**Alicia Polanco Risquet:** graduated in Engineering of Telecommunications in 1981 at Higher Polytechnic Institute of Havana, ISPJAE, Cuba. She obtained the MSc. Degree in microelectronics in 1985 and received the PhD degree in 2001. She has been an Assistant Researcher at the Microelectronics Research Center (CIME), ISPJAE, Cuba.



**Agnes Nagy:** graduated in physics from Havana University in 1971, received an MSc. In Microelectronics in 1978 and obtained the PhD. degree in 1998 al Higher Polytechnic Institute of Havana, (ISPJAE), Cuba. She has been an Assistant researcher at the Microelectronics Research Center (CIME), ISPJAE,

**Manuel Alvarez Blanco:** graduated in Engineering of Telecommunications in 1970 at Higher Polytechnic Institute of Havana, ISPJAE, Cuba. He obtained the PhD degree in 1988. He is professor at Higher Polytechnic Institute of Havana, ISPJAE, and is working as a collaborator in Microelectronics Research Center (CIME), ISPJAE, Cuba since 1998.