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Hybrid Algorithm for Using Bipolar Junction Transistors as Primary Thermometers

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Abstract. This work introduces a novel hybrid algorithm, which allows computing the absolute temperature of a bipolar transistor device in thermal equilibrium for sensing ambient temperature. The proposed idea relies on the measured current-voltage characteristics of the device and it can be implemented in any computing platform. Experimental data obtained, using a broad collection of commercial devices, demonstrates the accuracy of the proposed algorithm.

Keywords. Thermometer, temperature, bipolar junction transistor.

1 Introduction

For decades, P-N junction structures at forward bias has been used extensively for sensing ambient temperature. Nevertheless, P-N junctions are prone to non-desirable surface effects, as generation and recombination in the depletion layer.

Consequently, bipolar junction transistors (BJT), with collector to base short-circuit are preferred for temperature measurement applications, since these devices exhibit a current-voltage (I-V) characteristic, closer to a pure exponential function.

Often, due to their temperature coefficients, BJTs are used for the implementation of band-gap voltage references [1]. In this sense, Verster [2] proposed a methodology where two different collector current magnitudes, I_1 and I_2, are employed in a BJT circuit. The difference between both base-emitter voltages $\Delta v_{BE}=v_{BE1}-v_{BE2}=(kT/q)ln(I_1/I_2)$ (where k is Boltzmann's constant, q is the electron charge and T is the absolute temperature) is used to calculate the absolute temperature T, with inaccuracies of the order of 3K to 4K.

Other approaches, suggest the use of BJTs as primary absolute thermometers. The acquisition of an absolute temperature value without any calibration step has many advantages from the manufacture and cost perspective. Felimban *et al.* [3] introduced an absolute thermometer based on an emitter-base voltage characterization of a commercial BJT in the 77K-400K range. Using the short-circuit from collector to base as depicted in Fig. 1, the main component of BJT collector current is due to thermal diffusion of carriers. Therefore, the forward collector current is expressed by:

$$I_C = I_S(T)\exp[\beta(T)V_{BE}]\,, \tag{1}$$

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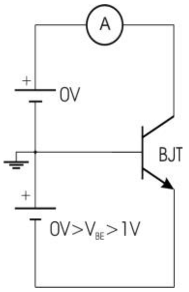

Fig. 1. BJT biasing with shorted collector-base junction

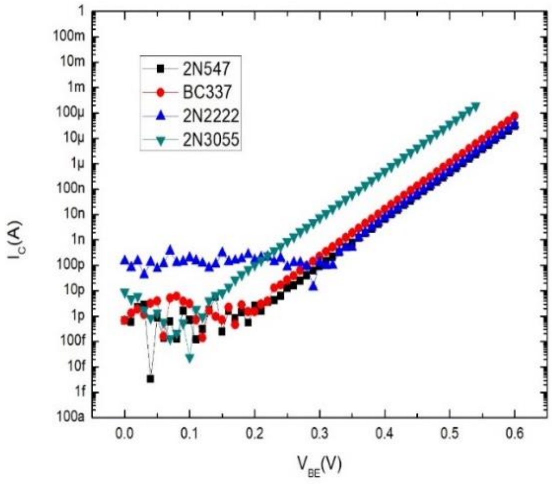

Fig. 2. Different I-V characteristics of commercial BJTs at 0ºC

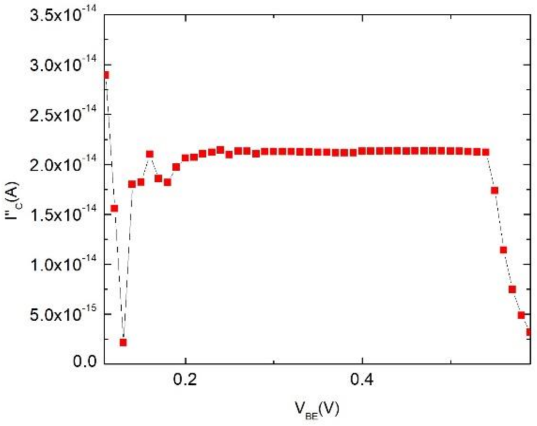

Fig. 3. Linear plot of I''_C vs. V_{BE} for $T^*=T$, the value of I_S=2.1129×10-14A was previously calculated using (2) at 273.15K

where $I_S(T)$ is the inverse saturation current and β is q/kT.

By using the BJT characterization data I_C vs. V_{BE} in a semilog-plot as done in [3], the absolute temperature can be computed, see Fig.2.

2 Computation of the Absolute Temperature

From the I-V characterization data, equation (1) can be rearranged to the linear form using the natural logarithm function, this is:

$$I'_C = \alpha + \beta V_{BE}\ , \tag{2}$$

where $I'_C=ln(I_C)$, $\alpha=ln(I_S)$ and V_{BE} is the independent variable. Therefore, with the measured data (I_C, V_{BE}), taken to the form (2) and by using a linear fit, the absolute temperature can be extracted from the slope β.

However, this methodology present important drawbacks. First, only those data points related closely to (1) must be considered, i.e. data points close to a straight line in the semi-log plot. Second, slope computation is very sensitive to noise especially for small currents; this eventually will produce an error of several Kelvin in the temperature calculation. However, (2) can be used to compute I_S accurately through α as the axis intercept.

Recently, Mimila-Arroyo [4] proposed a different methodology using an auxiliary numerical operator $exp[-\beta(T^*)V_{BE}]$ where T^* is a proposed temperature value. Again, from the BJT I-V characterization, the following expression can be formulated as the product of the collector current and the operator:

$$I''_C(T) = I_C(T)\cdot \exp[-\beta(T^*)V_{BE}]\,. \tag{3}$$

Consequently, by using (1) and (3) the following limit must be fulfilled:

$$\lim_{T^*\to T} I''_C(T) = I_S(T). \tag{4}$$

Since $I_S(T)$ has very little dependence with V_{BE}, it is expected that when $T^*=T$, the I''_C vs. V_{BE} plot turns into a straight line parallel to the abscissa axis, see Fig. 3. Thus, when this graphical condition is satisfied, the absolute temperature T is obtained. This methodology reports temperature errors in the mK range.

3 Hybrid algorithm

Following the methodology in [4-5], T^* must be adjusted manually until the graphical condition where a straight line parallel to the abscissa is obtained, in such case T is determined. Therefore, the proposed hybrid algorithm based on (2) and (4) is formulated in order to get a cost function, which allows numerically to find the absolute temperature in a fully automated fashion, the algorithm is as follows:

1. Select the data set from the BJT I-V characterization that is in the form of (1).
2. 2.-Determine IS using (2) through α using a linear fit.
3. 3.-Since (4) must be fulfilled when $T^*=T$, the following sum of squared errors can be considered as a cost function.

$$f(T^*) = \sum_{i=1}^{n}(I_S - I_{Ci}\exp[-\beta(T^*)V_{BEi}])^2 \ , \qquad (5)$$

where (I_{Ci}, V_{BEi}) is the *ith* I-V measurement pair. This function should have a global minimum when $T^*=T$ and can be find numerically by any optimization method.

4 Experimental Results

Several I-V measurements were conducted using commercial BJTs at different temperatures using Keithley 6487 picoammeter. A plot of the cost function $f(T^*)$ vs. T^* with the 2N2222 and 2N3055 devices at 0°C is depicted in Fig. 4. As it can be seen following (5), the cost function is a continuous function with a global minimum close to the absolute temperature 273.15K.

The comparison of real and computed temperatures, following the methodology, are depicted in Table I and Table II. Several commercial BJTs were tested at different temperatures in the -20°C to 100°C range. Measurements were conducted in the certificated laboratory of metrology MetAs S.A. de C.V.

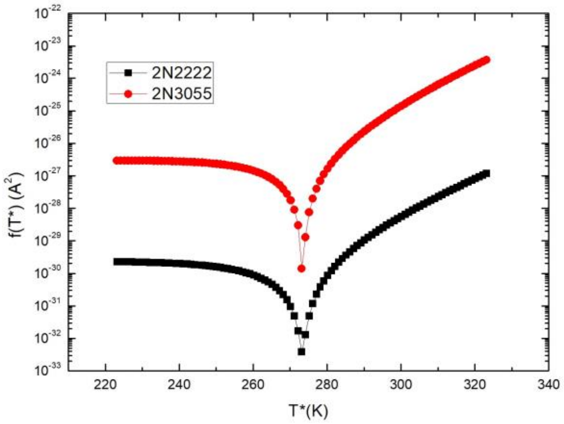

Fig. 4. Plot of cost function for two commercial BJTs in the -50°C to 50°C range expressed in K

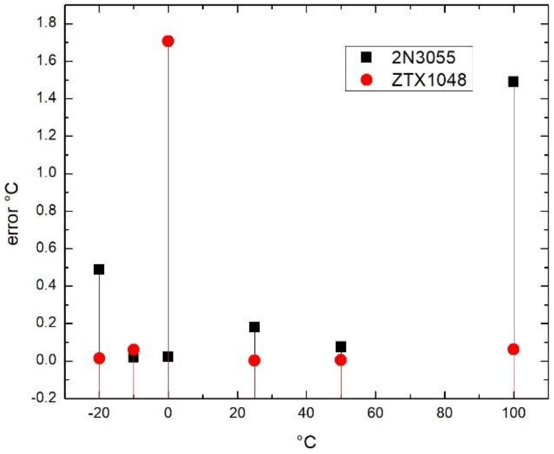

Fig. 5. Measured absolute error of 2N3055 and ZTX10 in the -20°C to 100°C range

5 Discussion

The proposed methodology was developed with the aim of avoiding the use of derivative based methods, since these introduce inaccuracies due to noise presence. Although the experimental results are not as accurate as those reported in [4], the results are quite good as compared with other methodologies including [6], where more complex I-V models were considered.

As part of this work, the series resistance *Rs* of base-emitter junction were characterized following

Table 1. Experimental results of commercial BJTs in -20°C to 0°C

Transistor Rs (Ω)	**-20°C**		**-10°C**		**0°C**	
	Temp./std dev. (°C)	**Computed Temp. (°C)**	**Temp./std dev. (°C)**	**Computed Temp.(°C)**	**Temp./std dev. (°C)**	**Computed Temp.(°C)**
BC547 0.792Ω	-19.996 /0.0048	-16.2369	-10.096 /0.0047	-8.3669	0.0033 /1.4e-4	0.4727
BC337 0.998Ω	-20.156 /0.0087	-15.2889	-10.0292 /0.0032	-4.1839	0.0037 /1.5e-4	0.4100
2N2222 0.924Ω	-20.110 /0.0168	-17.8339	-10.0412 /0.0012	-7.3799	0.0039 /1.5e-4	0.2324
2N3055 0.369Ω	-19.9226 /0.0146	-19.5119	-9.9514 /0.0293	-10.0190	0.0039 /1.9e-4	0.0226
ZTX1048 0.307Ω	-19.9831 /0.0098	-19.9857	-9.9811 /0.0101	-9.9407	0.0038 /1.6e-4	1.7054

Table 2. Experimental results of commercial BJTs in 25°C to 100°C

Transistor Rs (Ω)	**25°C**		**50°C**		**100°C**	
	Temp./std dev.	**Computed Temp. (°C)**	**Temp./std dev.**	**Computed Temp.(°C)**	**Temp./std dev.**	**Computed Temp.(°C)**
BC547 0.792Ω	25.006 /8.2e-4	25.8281	50.0294 /0.0068	52.3127	99.998 /0.0093	89.9970
BC337 0.998Ω	25.0136 /5e-4	26.9779	50.0348 /0.0055	50.9016	100.098 /0.0012	101.0970
2N2222 0.924Ω	25.0101 /4e-4	25.7463	50.0258 /.0056	50.9296	100.028 /0.0133	102.1494
2N3055 0.369Ω	25.0213 /.0073	24.8202	50.0102 /0.0092	49.9250	100.07 /0.0049	98.5100
ZTX1048 0.307Ω	25.009 /.0012	24.998	50.0312 /.0071	50.0053	100.051 /0.0112	100.0630

[7] for each transistor, Table I and Table II. This series resistance could be related with the high accuracy of 2N3055 and ZTX1048 as compared with the other transistors, probably, its I-V behavior is closer to (1) improving accuracy.

A secondary effect could be the package of the BJT which could help to dissipate the auto-heating effect in high currents. However, the 2N3055 with a low thermal resistance package does not show a lower absolute error over ZTX1048 as depicted in Fig. 5, in the -20°C to 100°C range. Further research of the series resistance role could help improving the accuracy.

6 Conclusions

A hybrid methodology for the calculation of the absolute temperature from the I-V characterization of a BJT is introduced. The proposed methodology can be implemented on any numeric platform and allows the use of any BJT as a primary thermometer in a certain range. The best experimental results was identified by employing the commercial BJT ZTX1048, showing the feasibility of the proposal methodology with temperature errors <0.07K in almost all the entire -20°C to 50°C range, see Fig. 5.

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References

1. **Allen, P.E. & Holberg, D.R. (2002*).*** *CMOS analog circuit design*. Oxford University Press, pp. 153– 159.
2. **Verster, T.C. (1968).** PN junction as an ultralinear calculable thermometer. *Electronics letters*, Vol. 4, No. 9, pp. 175–176.
3. **Felimban, A.A. & Sandiford, D.J. (1974).** Transistors as absolute thermometers. *Journal of Physics E. Scientific Instruments*, Vol. 7, No. 5, pp. 341–342.
4. **Mimila-Arroyo, J. (2013).** Free electron gas primary thermometer: the bipolar junction transistor. *Applied physics letters*, Vol. 103, No. 193509, pp. 1–4.
5. **Mimila-Arroyo, J. (2017).** The free electron gas primary thermometer using ordinary bipolar junction transistor approaches ppm accuracy. *Review of scientific instruments*, Vol. 88, No. 064901, pp. 1–4.
6. **Kanoun, O. (2000).** Modeling the p-n junction I-U characteristic for an accurate calibration-free temperature measurement. *IEEE Trans. on instrumentation and measurement*, Vol. 49, No. 4, pp. 901–904.
7. **Cheung, S. K. & Cheung, N. W. (1986).** Extraction of Schottky diode parameters from forward-voltage characteristics. *Applied physics letters*, Vol. 49, No. 2, pp. 85–87.

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