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The temperature characteristics of bipolar transistors fabricated in CMOS technology

Guijie Wang *, Gerard C.M. Meijer

Faculty of Information Technology and Systems, Delft University of Technology, Mekelweg 4, 2628 CD Delft, Netherlands

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Abstract

This paper presents the results of an experimental investigation of the temperature characteristics of bipolar transistors fabricated in CMOS technology. These results have to be known and understood to enable the design of high-performance temperature sensors and bandgap references in CMOS integrated circuits. The non-idealities of proportional to the absolute temperature voltage (V_{PTAT}) have been studied, and the results show that we can generate accurate PTAT voltages by optimizing the operating condition and layout of the transistors (error $< 0.1\%$). The measurement results of $V_{BE}(I_C, T)$ characteristics show that the existing theory for transistors fabricated in bipolar technology is also quite useful for bipolar substrate transistors fabricated in CMOS technology. We found that the temperature sensors and the bandgap references fabricated in CMOS technology might even be better than those fabricated in bipolar technology.

Keywords: CMOS; Bipolar substrate transistor; Temperature sensors; Bandgap references

1. Introduction

As compared to temperature sensors and bandgap references processed in bipolar technology, those fabricated in CMOS technology are becoming more and more attractive because of their low cost and compatibility with CMOS VLSI. To make the design of temperature sensors and bandgap references possible, we have to know the temperature characteristics of bipolar transistors fabricated in CMOS technology. Although many interesting designs of CMOS temperature sensors and bandgap reference circuits are presented in the literature [1,2], very little is known about the basic limitation of the accuracy of these circuits and their long-term stability.

The basic signals in the temperature sensors and the bandgap reference are the base emitter voltage V_{BE}, and the proportional to the absolute temperature (PTAT) voltage V_{PTAT}, which is the difference between two base emitter voltages under different bias current densities. The combination of these two signals is applied for temperature sensors and bandgap references [3]. The performance of a well-designed temperature sensor or bandgap reference circuit depends on the accuracy of these two basic signals.

In CMOS technology, two types of bipolar transistors can be realized: lateral bipolar and substrate bipolar transistors. The substrate bipolar transistor is preferred because it has a better exponential relationship between the base emitter voltage and the collector current [4].

This paper describes an experimental investigation of the temperature characteristics of the base emitter voltage and the PTAT voltage of bipolar substrate transistors fabricated in CMOS technology. Devices fabricated in 0.7- and 0.5-μm CMOS (Alcatel Microelectronics) have been investigated and the results are presented in the following sections. The analyses of the measurement results have been done for circuit design application.

2. Testing set-up

For CMOS bipolar substrate transistors, it is much easier to control the emitter current I_E than the collector current I_C. Therefore, besides characterizing the $V_{BE}(I_C, T)$ characteristics, it is also important to characterize the

* Corresponding author. Tel.: +31-15-2781083; fax: +31-15-2785922.
E-mail address: g.wang@its.tudelft.nl (G. Wang).

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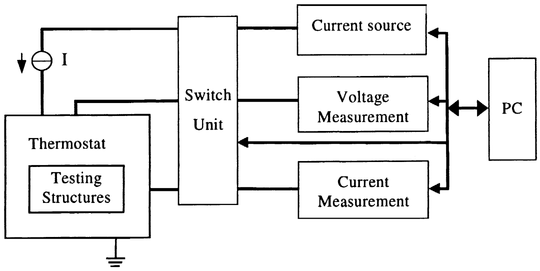

Fig. 1. The measurement set-up.

base-current effect: due to the low current gain of the bipolar substrate transistors, the base current has a significant effect. The non-idealities that affect the accuracy of V_{PTAT}, such as the base resistance, the effective emission coefficient and the low-level injection effect have been investigated by measuring V_{PTAT}. It has been investigated how the geometry and biasing current of the transistors can be optimized.

Fig. 1 shows a schematic of the measurement set-up for the $V_{PTAT}(I, T)$ and $V_{BE}(I, T)$ characterizations. The biasing currents I_E, the base currents I_B, the voltages V_{PTAT} and V_{BE} are measured for different temperatures.

For our investigations and experiments, we selected a temperature range of -40°C to 160°C. For the biasing current range, we have chosen a range of 5 nA–1 mA for the base emitter voltage measurement and 5 nA–100 μA for the PTAT measurement, respectively. The current range is limited by practical constraints. These are due to the low-level effects, interference and $1/f$ noise at the low end, and to the high-level effects and power dissipation at the high end. The desired accuracy of all measurements corresponds to a temperature error of less than 0.1°C.

To realize accurate voltage and current measurements, we used an auto-calibration technique to eliminate the offset and gain error of the measurement set-up [5].

By the thermal design of the testing set-up, an accurate control and measurement of the temperature has been realized. In this design, particular care has been taken to minimize the temperature gradients and drift during the measurement.

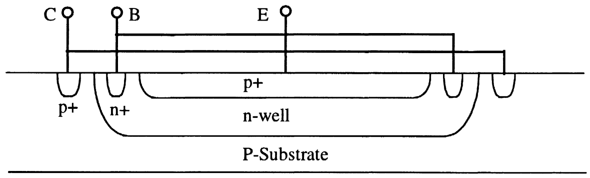

Fig. 3. The cross section of the substrate bipolar transistor (not to scale).

The test structure for the V_{PTAT} characterization consists of a pair of transistors with identical emitter size. The mismatching of the transistors will cause an error in the V_{PTAT} measurement. This error has been eliminated by employing the dynamic element matching technique. This has been realized by interchanging the two transistors and taking the average of the measured PTAT voltages under the same biasing condition [1].

Fig. 2 shows a photograph of the test structure. On this chip, a single bipolar substrate transistor and a pair of transistors in a quad configuration have been realized to characterize $V_{BE}(I_C, T)$ and $V_{PTAT}(I_C, T)$ behavior. The size of the emitter is 10 μm × 20 μm.

Fig. 3 shows a cross-section of the substrate bipolar transistor in N-well CMOS technology.

3. Parameters derived from $V_{BE}(T)$ characterization

3.1. The parameters V_{g0} and η

Fig. 4 shows the measured results for $V_{BE}(I_C, T)$ of a bipolar substrate transistor fabricated in 0.7-μm CMOS technology. A good exponential relation is found between V_{BE} and I_C over several decades of currents.

The basic equation describing the $I_C(V_{BE}, T)$ dependency is:

$$I_C = I_S \exp^{\frac{qV_{BE}}{kT}}, \tag{1}$$

where k is the Boltzmann constant, T is the absolute temperature, q is the electron charge and I_S the saturation current of the bipolar substrate transistor. The saturation

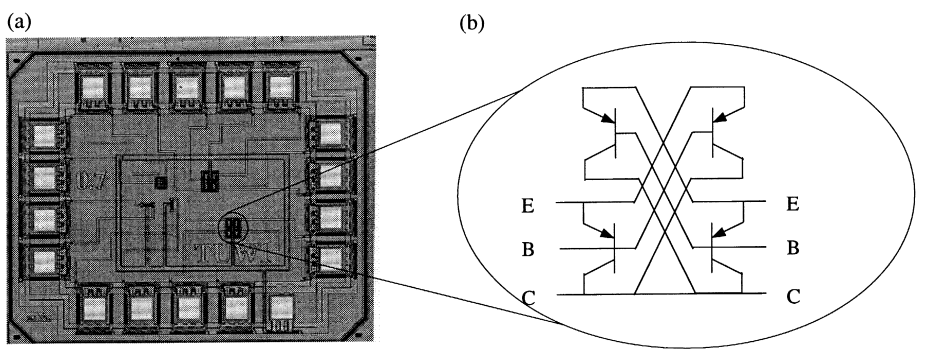

Fig. 2. (a) A photograph of the test devices; (b) the tested transistor pairs are constructed in a quad configuration.