Compact Low-voltage PTAT-Current Source and Bandgap-Reference Circuits

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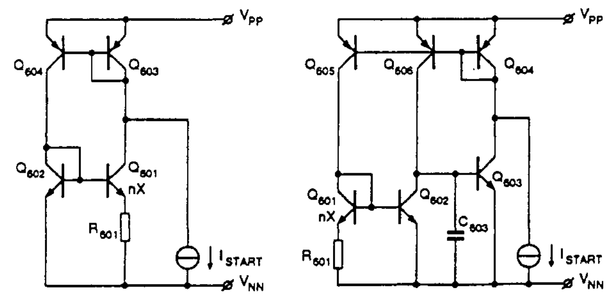
Abstract

A compact PTAT current source is described that can operate on supply voltages down to 1.3 V does not need a compensation capacitor and achieves good supply rejection. The PTAT circuit is used to implement several bandgap-reference circuits. In addition, bandgap circuits based on conventional PTAT sources are designed as a reference. The circuits have been implemented in a 1-μm BiCMOS process.

1. Introduction

PTAT current sources are widely used to generate bias currents and as temperature sensor in temperature measurement systems. They are also employed in bandgap reference circuits which are commonly used to generate temperature independent bias voltages and as reference in measurement systems.

Existing PTAT current sources are either based on the well-known circuit shown in Fig. 1a or on the current source with improved performance depicted in Fig. 1b. The first circuit has a low supply rejection because the collector voltages of the PTAT transistors Q_{601}, Q_{602} are not equal and the collector voltages of the current-mirror transistors Q_{603}, Q_{604} are not equal. The problem can be solved by inserting cascodes, but this increases the minimum allowable supply voltage. Therefore, the circuit shown in Fig. 2b has been devised combining operation to low supply voltage with high supply rejection[1]. However, this circuit uses a feedback loop which must be stabilized using a compensation capacitor increasing the die are. Further, both circuits require a start-up current. The start-up current of the circuit shown in Fig. 1a affects the performance of the current source and therefore the



a. b.

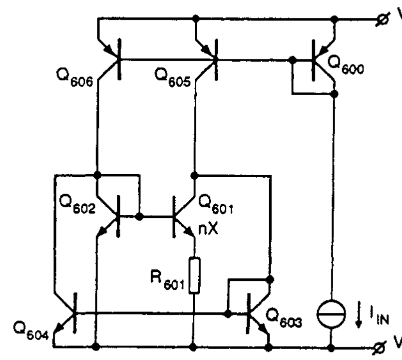
Figure 1. Conventional PTAT circuits

start-up current must be relatively small. consequently, large resistors are needed. The PTAT source described in this paper achieves good supply rejection without using a feedback loop. Instead of a start-up current, an input current is required that does not affect the PTAT current in first order as long as the input current is larger than the PTAT current to be generated.

In Section 2 the compact PTAT current-source principle is described while in Section 3 bandgap reference circuits are discussing that use the compact PTAT source. In addition, Bandgap circuits applying conventional PTAT circuits are discussed. The complete implementations of the compact PTAT current source and the bandgap reference circuits are presented in Section 4 and, finally, in Section 5 the conclusion are drawn.

2. Compact PTAT circuit

Referring to Fig. 1a, the problem of the different collector-emitter voltages of Q_{601}, Q_{602} and Q_{603}, Q_{604} can be easily solved by replacing the PNP current mirror Q_{603}, Q_{604} by a folded NPN current mirror yielding the compact PTAT current source. The circuit consists of a



PTAT

Figure 2. Compact PTAT principle

transistor pair Q_{601}, Q_{602} and an NPN current mirror Q_{603},Q_{604} in parallel. Two equal current sources Q_{605} and Q_{606} are required with a value larger than the PTAT current. In that case, the PTAT current is given by

$$I_{PTAT} = \frac{kT \ln(n)}{q \quad R_{601}} \qquad (1)$$

where k is Boltzmann's constant, T is the temperature q is the electron charge and n is the emitter ratio between transistors Q_{602} and Q_{601}. The current I_{PTAT} flows through Q_{601} and Q_{602} and the remaining current flows through the mirror Q_{603}, Q_{604}. The circuit does not employ a feedback loop and therefore does not require a compensation capacitor. Further, all the collector-emitter voltages of the PTAT transistors are nearly equal so that a high supply rejection is obtained. In first order I_{PTAT} is independent of the input current I_{IN}. However, because Q_{602} is biased by the constant voltage its base current and base-emitter voltage are constant. Transistor Q_{603}, on the other hand, is biased by the remaining current which is directly proportional to I_{IN}. Therefore its base current and its base-emitter voltage change as a function of I_{IN}. Thus, I_{IN} should be relatively constant over the supply voltage range. A possibility is to use a peaking-current source to create the input current I_{IN}.

3. Compact bandgap circuits

A constant reference voltage can be obtained by connecting a base-emitter voltage with negative temperature coefficient in series with a resistor biased by a PTAT current. The resulting reference voltage is of the order of 1.2V[2] When we use the conventional PTAT source as shown in Fig. 1a, the reference voltage can simply be created by connecting a resistor in series with the negative supply connection V_{NN} as shown in Fig. 3[3]. The PTAT current which flows through Q_{601} and Q_{602} flows through R_{602} and generates a voltage with positive temperature coefficient. The voltage across R_{602} compensates the negative temperature coefficient of the base-emitter voltage of Q_{602} yielding a reference voltage V_{REF} that is independent of temperature.

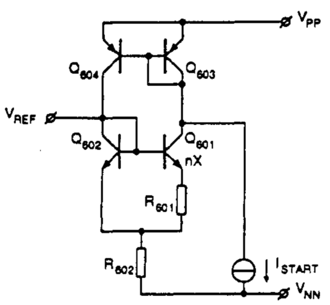


Figure 3. Conventional bandgap circuits

The same technique can be applied using the compact PTAT source yielding the circuit shown in Fig. 4. Again, a resistor, R_{610}, is connected between the PTAT cell R_{601}, Q_{601}, Q_{602} and the negative supply connection so that the PTAT current flows through R_{610}. Together with the base-emitter voltage of Q_{602} the reference voltage is obtained. Emitter resistors R_{603}, R_{604} haven been added to the current mirror Q_{603}, Q_{604} in order to make the voltages at the collectors of Q_{601} and Q_{602} equal.

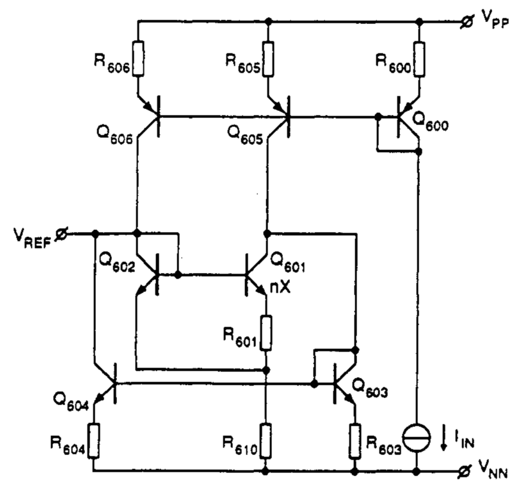


Figure 4. Compact bandgap circuit

A slightly modified circuit is shown in Fig. 5 where a voltage follower Q_{612} is used to obtain a buffered output. Transistor Q_{612} is biased using diode-connected transistor Q_{622} and resistor R_{622}. Drawback of the circuit is that due to the follower Q_{612} the minimum supply voltage is increased by a base-emitter voltage.

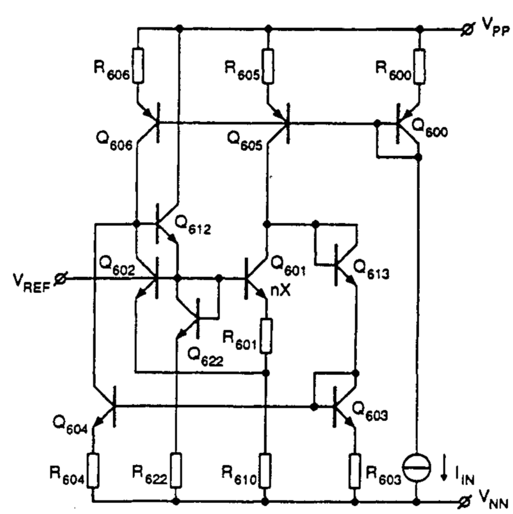


Figure 5. Bandgap circuit with output buffer

The same technique that is used to obtain the bandgap circuit shown in Figs. 3 and 4 can also be applied to the PTAT circuit which is shown in Fig. 1b yielding an interesting circuit as shown in Fig. 6. The circuit is compact and can achieve high performance. But, the reference-voltage output cannot be loaded. Any capacitive load connected to the output results in oscillations. Therefore an output buffer circuit is required.

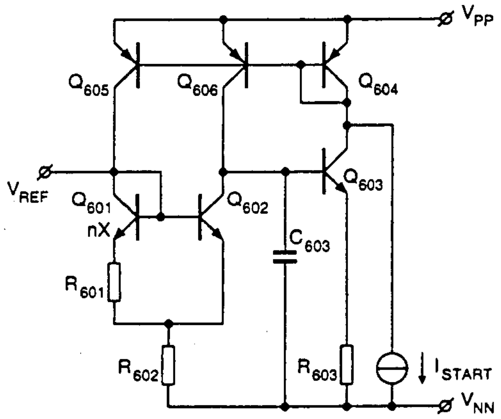


Figure 6. Bandgap circuit based on PTAT source of Fig. 1b

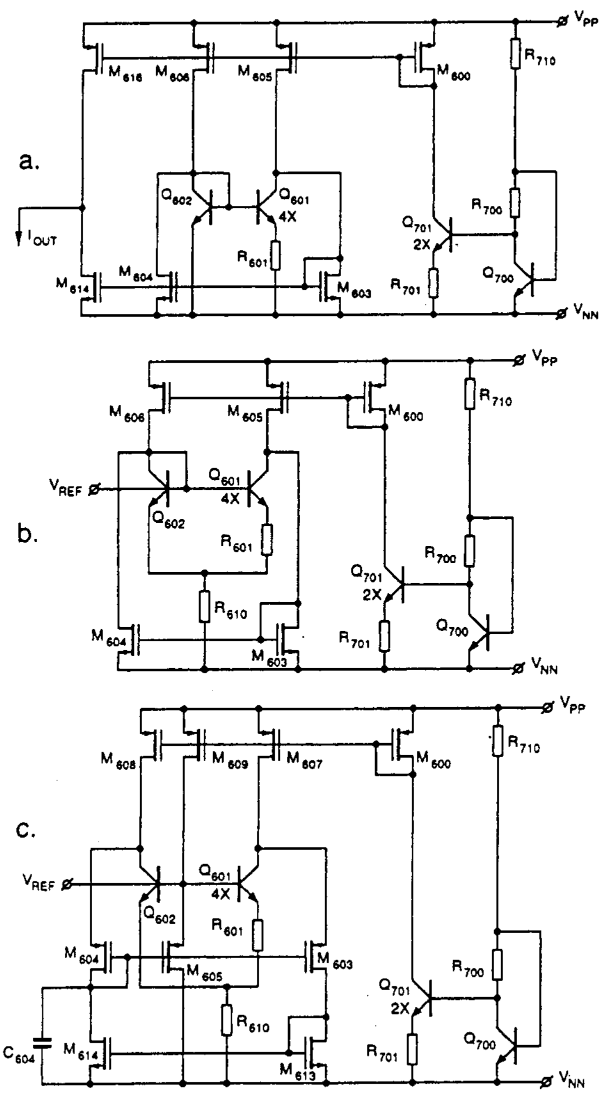


Figure 7. Implementations

4. Implementations

Several test circuit have been implemented in a 1-μm BiCMOS process. The schematics of the circuits are shown in Fig. 7 and Fig. 8. The PTAT current source based on the principle shown in Fig. 2 is depicted in Fig. 7a. The input current is created by a peaking-current source Q_{700}, Q_{701}, R_{700}, R_{701}, R_{710}. The peaking current source creates a current that is only weakly dependent on the supply voltage. To prevent influence of base-currents the current sources and the current mirror are implemented using MOS transistors. The PTAT output current is created by subtracting the current flowing through the current source M_{605}, M_{606} from the current flowing through the current mirror M_{604}, M_{603} using transistors M_{614} and M_{616}. Thus the output current is equal to the current flowing through Q_{602}.

The bandgap circuit based on the circuit shown in Fig. 4 is presented in Fig. 7b(BG1). A buffered version of the bandgap circuit is shown in Fig. 7c(BG2). The buffer is implemented using voltage follower M_{605} and levelshift M_{604}. By using the levelshift the minimum supply voltage is not increased by adding the buffer circuit.

A bandgap circuit based on the conventional circuit shown in Fig. 3 is depicted in Fig. 8(BG3). Cascodes are applied to improve the supply rejection but this increases the minimum supply voltage.

A Photomicrograph of the test chip is shown in Fig. 11 and the measurements result are depicted in Figs. 9 and 10. The output current of the PTAT current source is plotted as a function of the supply voltage in Fig. 9a together with the input current. The plot demonstrates the good supply rejection while the input current created by the peaking current source displays considerable variation. The current as a function of temperature shows the proportional to absolute temperature behavior of the current source as depicted in Fig. 9b. An overview is given in Table 1. The reference voltage as a function of temperature of the three bandgap circuits is shown in Fig. 10 and an overview of the result of the bandgap circuits is given in Table 2. The circuits show good behavior compared to the conventional bandgap circuit, but they are smaller and can operate down to 1.6V instead of 2.3V. Due to the high input current the current consumption is rather high, but this can be improved by applying a different input current source.

5. References

[1] H.C. Nauta and E.H. Nordholt, "New Class of High-Performance PTAT Current Sources", Electronic Letters, Vol. 21, 1985, pp. 384-386.

[2] G.C.M. Meijer, "Bandgap references" in J.H. Huijsing et al., *Advances in Analog Circuit Design*, Kluwer Academic Publishers, Dordrecht, The Netherlands, 1995, pp. 243-268.

[3] A.P. Brokaw, "A Simple Three-Terminal IC Bandgap Reference", *IEEE J. Solid-State Circuits*, Vol. SC-9, No. 6, Dec. 1974. pp. 388-393.

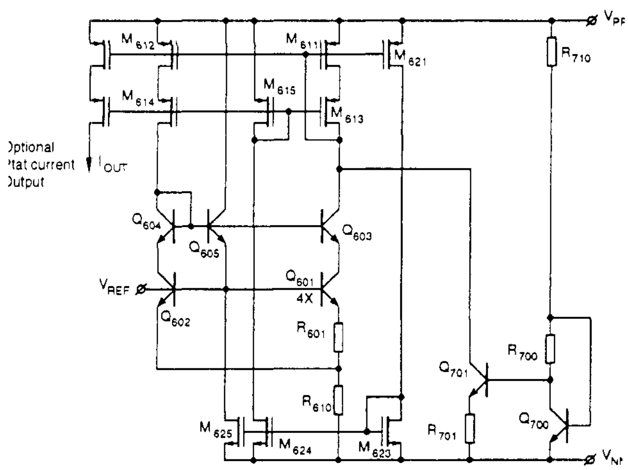


Figure 8. Implementation based on conventional circuit

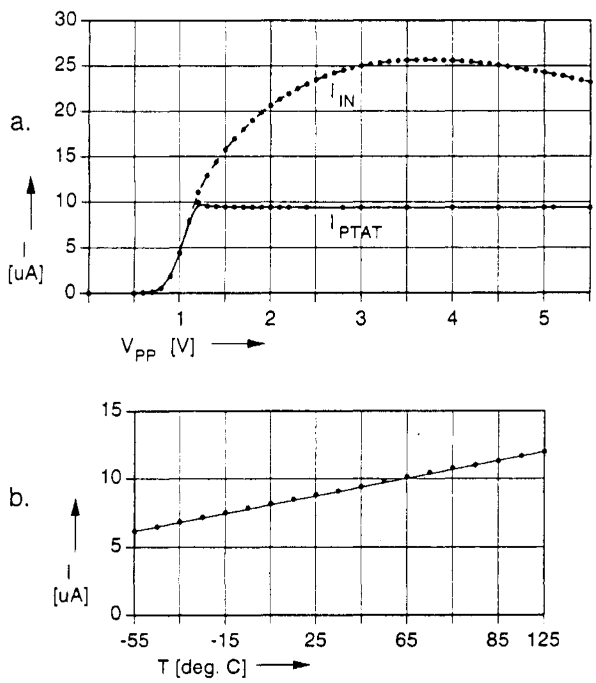


Figure 9. Measurements of PTAT circuit

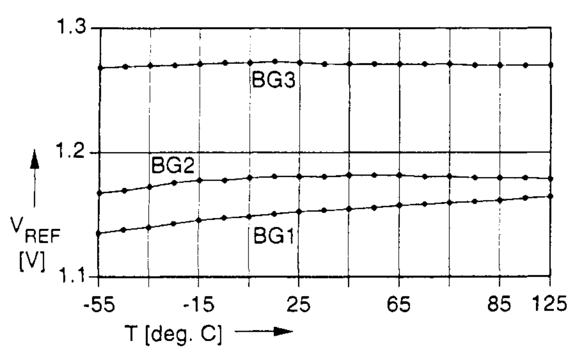


Figure 10. Measurements of bandgap circuits

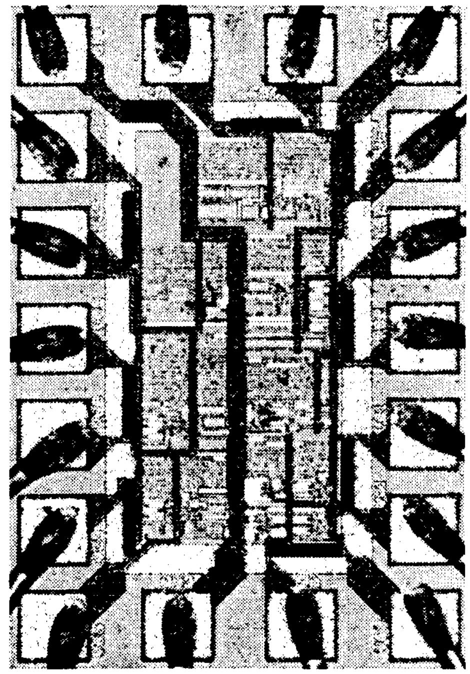


Figure 11. Photomicrograph of test chip

Table 1. Measured Specifications of PTAT circuit. V_{PP}=3 V, T_A=27 °C unless otherwise stated

parameter	value			unit
	nom	min	max	
Die area	8			(x1000 μm^2)
supply voltage		1.3	5.5	(V)
supply current	100	140	190	(μA)
output current	9.5	8.8	10.0	(V)

Table 2. Measured Specifications of bandgap circuits. V_{PP}=3 V, T_A=27 °C unless otherwise stated

parameter		circuit			unit
		1	2	3	
Die area		15.6	17.6	20.1	(x1000 μm^2)
supply voltage	max	5.5	5.5	5.5	(V)
	min	1.6	1.5	2.3	
supply current		115	127	48	(μA)
reference voltage	nom	1.17	1.26	1.19	(V)
	max	1.23	1.27	1.195	
	min	1.14	1.25	1.17	
noise (f = 10 kHz)		730	650	220	$(nV/\sqrt{Hz})$