A 2.2-V 2.9-ppm/℃ BiCMOS bandgap voltage reference with full temperature-range curvature-compensation

Zhou Zekun(周泽坤)†, Ma Yingqian(马颖乾), Ming Xin(明鑫), Zhang Bo(张波), and Li Zhaoji(李肇基)

(State Key Laboratory of Electronic Thin Films and Integrated Devices, University of Electronics Science and Technology of China, Chengdu 610054, China)

Abstract: A high precision high-order curvature-compensated bandgap reference compatible with the standard BiCMOS process, which uses a simple structure to realize a novel exponential curvature compensation in lower temperature ranges, and a piecewise curvature correction in higher temperature ranges, is presented. Experiment results of the proposed bandgap reference implemented with a 0.6-μm BCD process demonstrate that a temperature coefficient of 2.9 ppm/°C is realized at a 3.6-V power supply, a power supply rejection ratio of 85 dB is achieved, and the line regulation is better than 0.318 mV/V for 2.2–5 V supply voltage dissipating a maximum supply current of 45 μA. The active area of the presented bandgap reference is 260 × 240 μm^2.

Key words: high-order curvature compensation; exponential curvature compensation; piecewise curvature compensation; BiCMOS bandgap reference; temperature coefficient; PSRR

DOI: 10.1088/1674-4926/31/7/075004 **EEACC:** 1130B; 1205

1. Introduction

Precision bandgap references play an important role in many applications ranging from purely analog, mixed-mode to purely digital circuits, such as A/D converters, DRAMS, power converters and flash memory controlling circuits for their high accuracy and temperature independence[1–3]. The reference voltage is required to be stabilized over the supply voltage and temperature variations, and also to be implemented without modification of the fabrication process[1].

The traditional bandgap reference circuit is first-order temperature compensated. It is a weighted sum of negative TC voltage V_{BE}, and positive TC voltage V_T which is the thermal voltage kT/q. With regard to the nonlinearity of the voltage V_{BE}, the TC of first-order temperature compensated references is always limited between 20 and 100 ppm/°C[3–6]. In order to overcome the limitation, many high-order temperature compensation approaches have been developed, such as quadratic temperature compensation proposed by Song *et al.*[7], exponential temperature compensation developed by Lee *et al.*[3], piecewise-linear curvature correction presented by Rincon-Mora *et al.*[4, 8], and temperature dependent resistor ratio with high resistive poly resistor and a diffusion resistor by Leung *et al.*[2]. Although the temperature stability of the bandgap references have been improved with those techniques, it increases the requirements of precise matching of current mirror, pre-regulated supply voltage, or high resistive resistance.

In order to attain low TC in a full temperature range, a novel curvature compensation technique combined with exponential curvature compensation and piecewise curvature compensation is described in this paper. The two compensation methods are used to improve the performance of temperature drift in lower temperature and higher temperature respectively. Based on the compensation technique, a high-order curvature-compensated with high performance BiCMOS bandgap reference is presented by a simple circuit structure in this paper. It eliminates the impact of resistances' temperature coefficient on the circuit by using resistance ratios.

2. Proposed curvature compensation method

The relationship between the collector current and base-emitter voltage V_{BE} of npn BJTs, which are biased in the forward active region, can be expressed as[5, 9]

$$V_{BE}(T) = V_{G0} - mV_T - (\eta - \alpha)V_T \ln T, \quad (1)$$

where m is temperature-independent constant, α is the order of the temperature dependence of the collector current, V_T is the thermal voltage, and V_{G0} is the bangap voltage of silicon extrapolated to 0 K. $\eta = 4 - n$, n is the exponent of the relationship between mobility in the base and temperature, η is always between 3 and 4 with the most representative value 3.45[10]. From Eq. (1), the $V_T \ln T$ term demonstrates the high-order nonlinearity of V_{BE}, when it is expanded in Taylor series at T_r, it can be represented by

$$V_T \ln T = \frac{k}{q}\big[(T - T_r) + \frac{1}{2}(T - T_r)^2 - \frac{1}{6}(T - T_r)^3 + 1/12 \times (T - T_r)^4\big]. \quad (2)$$

First-order temperature compensation involves the cancellation of the T term while high-order temperature compensation involves the cancellation of high-order T terms. This results in the realization that a high-order compensated bandgap reference cannot be achieved only by conversional linear compensation.

The method of proposed curvature compensated bandgap reference core is shown in Fig. 1. All the resistances are made

† Corresponding author. Email: zkzhou@uestc.edu.cn
Received 23 December 2009, revised manuscript received 21 February 2010

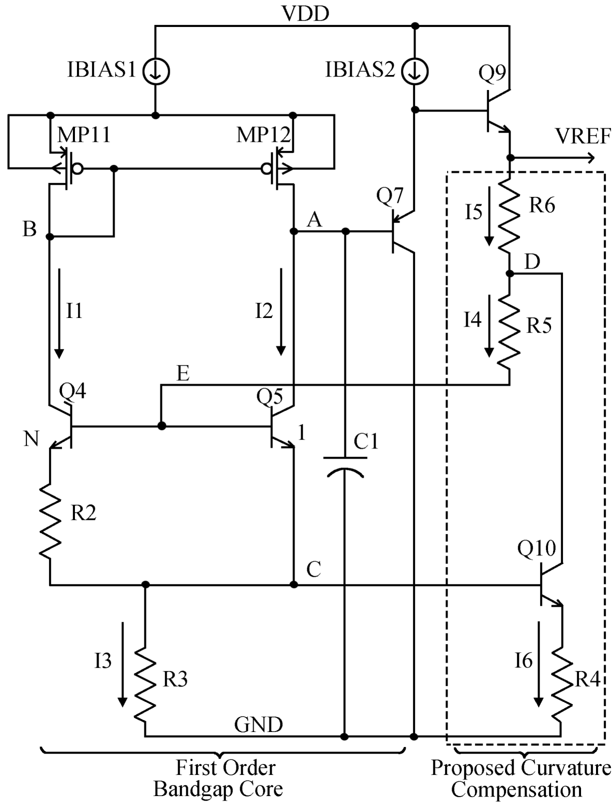

Fig. 1. Schematic of proposed bandgap reference core.

by the same material. For the convenience of description, the TC of the resistances is ignored temporarily, and the influence of the resistances' temperature coefficient on the bandgap reference will be considered at the end of the analysis. The left part of the proposed bandgap reference is similar to a conventional first-order temperature compensated reference. Similarly, the voltage of node E is a first-order temperature compensated reference, $V_E = V_{BE5} + \frac{R_3}{R_2} V_T \ln N$, and the voltage of node C is a PTAT voltage, $V_C = \frac{R_3}{R_2} V_T \ln N$.

In this way, the BJT Q10 is turned off in the lower temperature range, where the voltage of node C is smaller than the turn-on voltage of Q10. The output voltage V_{REF} in the lower temperature range can be given by

$$V_{REF} = V_{BE5} + \frac{R_3}{R_2} V_T \ln N + 2\frac{(R_5 + R_6)\ln N}{R_2} \frac{V_T}{\beta(T)}, \quad (3)$$

where the term $2(R_5 + R_6)V_T \ln N/R_2\beta(T)$ is the voltage drop at R_5 and R_6 due to the base currents of Q4 and Q5, and it makes a nonlinear curvature compensation voltage. The temperature dependency of $\beta(T)$ is an exponential function of temperature, and an inverse exponential function of the emitter doping level[11–13]. It can be expressed as[13]

$$\beta(T) = \beta_\infty \exp\left(-\frac{\Delta E_G}{kT}\right), \quad (4)$$

where ΔE_G is the bandgap narrowing factor of emitter proportional to the emitter doping level, and k is the Boltzmann's constant. Combining Eqs. (3) and (4), the curvature-compensated bandgap reference can be generated as

$$V_{REF} = V_{BE5} + \frac{R_3}{R_2} V_T \ln N + 2\frac{(R_5 + R_6)\ln N}{R_2\beta_\infty} V_T \exp\frac{\Delta E_G}{kT}. \quad (5)$$

The high-order curvature-compensation term $2(R_5 + R_6)V_T \exp(E_G/kT)\ln N/R_2\beta_\infty$ expanded in Taylor series at T_r can be derived as

$$2\frac{(R_5 + R_6)\ln N}{R_2 R_\infty} V_T \exp\frac{\Delta E_G}{kT} = a_0 + a_1(T - T_r)^2 - a_2(T - T_r)^3 + a_3(T - T_r)^4, \quad (6)$$

where a_0, a_1, a_2, and a_3 are temperature-independent constants. Considered with Eqs. (1), (2), (5), and (6), the curvature-compensation term behaves as a somewhat complicated function of temperature since the term to cancel the curvature of V_{BE} has many higher order terms in itself. By properly setting the resistance ratios of R_3/R_2 and $(R_5 + R_6)/R_2$, the TC of the proposed bandgap reference can be optimized.

In the higher temperature range, the negative TC of voltage V_{BE} increases greatly, and that can result in the output voltage V_{REF} decreasing with temperature. For the sake of improving the performance of temperature drift in higher temperature range further, a piecewise curvature correction is realized trough R_4, R_6 and Q10. The turn-on voltage of Q10 decreases with the temperature rising because of the characteristic of V_{BE}, and the voltage of node C increases with temperature rising. The Q10 is turned on at the temperature where the voltage of node C is larger than the turn-on voltage of Q10, viz. $V_{BE10}(T_1) = (R_3/R_2)V_{T1}\ln N$. According to Fig. 1, the output voltage V_{REF} in higher temperature range can be given by

$$V_{REF} = V_{BE5} + \frac{R_3}{R_2} V_T \ln N + 2\frac{(R_5 + R_6)\ln N}{R_2\beta_\infty} V_T \exp\frac{\Delta E_G}{kT} + \frac{R_6}{R_4}\left(\frac{R_3}{R_2} V_T \ln N - V_{BE10}\right). \quad (7)$$

As a result, an additional positive TC term is added to the bandgap reference for alleviating the increased negative TC of V_{BE}.

The output voltage of proposed bandgap reference can be described by

$$f(x) = \begin{cases} V_{BE5} + K_1 V_T + K_2 V_T \exp\dfrac{\Delta E_G}{kT}, & T < T_1, \\ V_{BE5} + K_1 V_T + K_2 V_T \exp\dfrac{\Delta E_G}{kT} + K_3(K_4 V_T \ln N - V_{BE10}), & T \geqslant T_1, \end{cases} \quad (8)$$

where $K_1 = R_3 \ln N/R_2$, $K_2 = 2(R_5 + R_6)\ln N/R_2\beta_\infty$, $K_3 = R_6/R_4$, $K_4 = R_3/R_2$. By properly adjusting the parameters in Eq. (8), the TC of the proposed bandgap reference can be optimized. Thereby, the high-order curvature-compensated bandgap reference circuit is realized by a simple structure without many additional circuits shown in Fig. 1, and the TC of the output voltage is zero at some temperatures. The presented

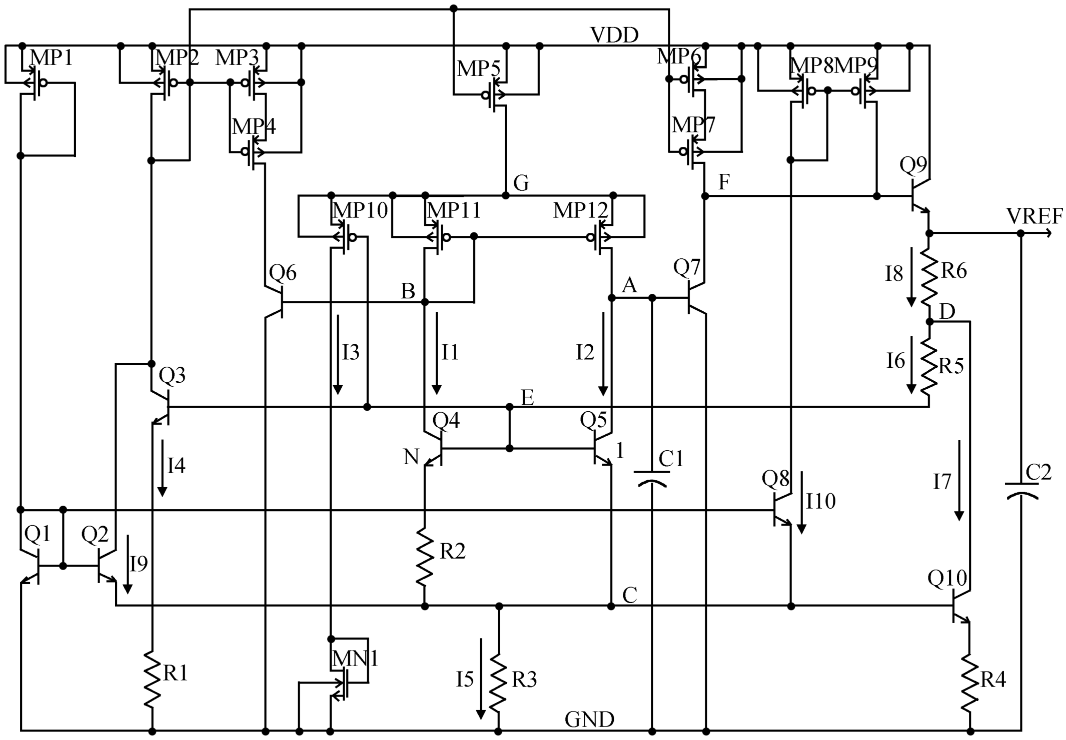

Fig. 2. Complete schematic of the proposed bandgap voltage reference.

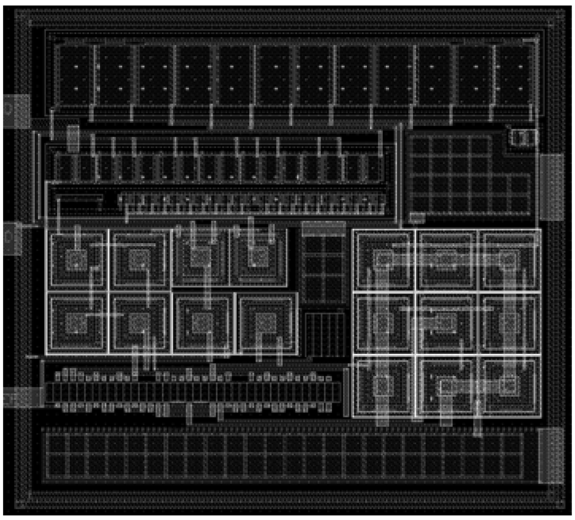

Fig. 3. Layout of the proposed bandgap reference.

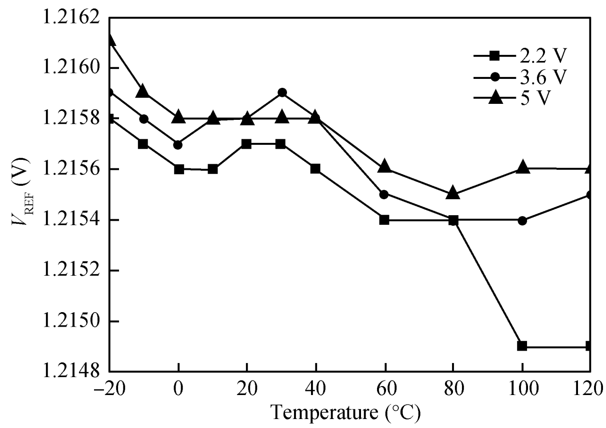

Fig. 4. Measured temperature dependence of the proposed bandgap voltage reference.

bandgap voltage reference can maintain a low temperature drift in the full temperature range. Equation (8) indicates that all the resistances used in the circuit appear in the form of resistances ratios. Therefore, the temperature coefficient of the resistances has no influence on the reference output voltage by using the same type resistances.

BJTs Q7, Q9, and resistances R_5, R_6 form a negative feedback loop to improve the performance of the proposed bandgap reference. Q7 is used to improve the output resistance at node A, and the capacitance C_1 is added at node A to determine the dominant pole of the feedback loop for stability. The loop transfer function can be described as

$$T_0 \approx \left[\frac{g_{\mathrm{m5}}}{1+2g_{\mathrm{m5}}R_3} - \frac{g_{\mathrm{m4}}}{1+g_{\mathrm{m4}}(2R_3+R_2)}\right] \times [\beta_5 r_{\mathrm{o5}}||(r_{\mathrm{o12}}+r_{\mathrm{oI_{BLAS1}}})], \tag{9}$$

$$P_{\mathrm{dominant}} = \frac{1}{2\pi[\beta_5 r_{\mathrm{o5}}||(r_{\mathrm{o12}}+r_{\mathrm{oI_{BLAS1}}})]C_1}. \tag{10}$$

3. Circuit realization

The implementation of the overall circuit is illustrated in Fig. 2. The full temperature-range curvature compensation method is realized as the same as that shown in Fig. 1. BJT Q6 is used to compensate the base current of Q7, and make

Table 1. Comparison of simulation and measurement performances.

Parameter	Simulated results	Measured results
Supply current (μA)	38 (max)	45 (max)
VREF (V)	1.2276	1.2155
TC (ppm/℃)	1.3–2.3	2.9–5.3
Line regulation (mV/V)	0.034	0.318
PSRR @ DC (dB)	−95	−85

the voltages of nodes A and B equal. So the error of current mirror formed by transistors MP11 and MP12 is almost zero, the currents I_1 and I_2 are equal. The current I_4 is used to form the bias current shown in Fig. 1. The branch composed with transistors MP10 and MN1 acts as a current balancing path to guarantee that current in transistor MP5 has no influence on the current I_1 and I_2. The capacitance C_2 is used to filter some disturbance signals, and stabilize the bandgap reference output voltage.

The start-up circuit of the proposed bandgap voltage reference comprises of MP1, MP8, MP9, Q1, Q2, and Q8. As the voltage of node C is low at the beginning of start-up process, Q2 and Q8 turn on, and there will be current following into nodes C, F, and G. Therefore, the bandgap reference is driven towards the desired stable state. The start-up circuit can be turned off without any influence on the normal operation of the proposed bandgap reference, when the voltage of node C excesses some amount.

4. Experimental results and discussion

The proposed bandgap reference shown in Fig. 2 has been implemented in 0.6-μm BCD technology with minimum emitter size of 2 × 2 μm^2. 5 × 5 μm^2 pnp transistor and npn transistor, which are 6.25 times as large as the minimum transistor, were used as unit transistors to increase matching properties. The V_{THN} and $|V_{THP}|$ of this process is about 0.665 V, 0.806 V at 0 °C respectively. The layout of the proposed bandgap reference is shown in Fig. 3, and the active area is 260 × 240 μm^2. The temperature dependence of the reference voltage is illustrated in Fig. 4. The output voltage V_{REF} of the proposed bandgap reference has a deviation of 0.041% with temperature ranging from –20 to 120 ℃ at 3.6-V power supply. The temperature coefficient is 2.9 ppm/°C at 3.6 V and the maximum temperature coefficient is 5.3 ppm/℃ with power supply ranging from 2.2 to 5 V. It should be noted that there is only a small change on the reference voltage. This is due to the advanced compensation technology presented in this paper.

The measured supply dependence at –20, 30, and 120 ℃ is shown in Fig. 5. The output voltage deviation of the proposed bandgap reference is within 1.2 mV when the power supply voltage changes from 2.2 to 5 V, and the line regulation is less than 0.318 mV/V in the temperature range of –20 to 120 ℃. This profit from the well-matched current branches ensured by the two branches composed with Q6 and Q7, and the high gain of feedback loop. What's more, the transistor MP5 works as a pre-regulator to stable the voltage of node G to enhance the stability of the proposed bandgap reference.

The simulation and measurement performances are compared in Table 1. The difference between the mean values of reference voltage is mainly due to the bipolar transistor model

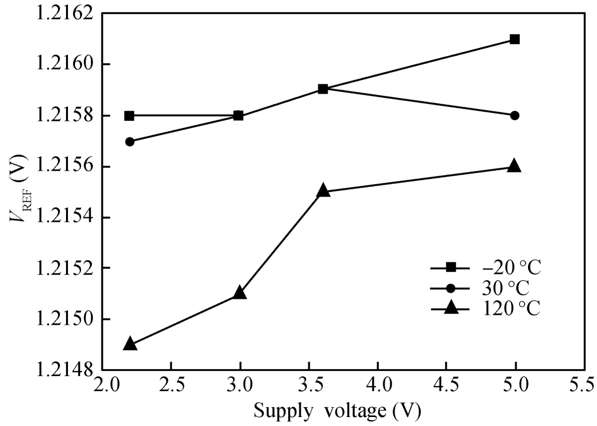

Fig. 5. Measured supply voltage dependence of the proposed bandgap voltage reference at different temperatures.

provided by the foundry. Table 2 summarizes a brief comparison on the results of proposed bandgap reference and the other voltage references reported in literature to show the improvements from the proposed structure.

5. Conclusion

Based on full temperature-range curvature compensation, a high precision high order curvature compensated CMOS bandgap voltage reference has been proposed and implemented with standard 0.6-μm BCD technology. Utilizing compensation items combined with exponential curvature compensation and piecewise curvature compensation to compensate the high order TC of V_{BE}, a high-order curvature-compensated BiCMOS bandgap voltage reference dissipating a maximum supply current of 45 μA is presented by the artful use of simple circuit structures. With the improvement mentioned above, the temperature coefficient of the proposed circuit is 2.9 ppm/℃ over the temperature range from –20 to 120 ℃ at 3.6-V power supply. The output reference voltage achieves 85-dB PSRR with a 3.6-V power supply at room temperature, and exhibits a line regulation better than 0.318 mV/V. The additional circuitry required for this correction is compact and is easily implemented. The architecture also lends itself to versatile trimming procedures. The proposed bandgap reference is well suited for many mixed signal systems for its high precision and high performance.

References

[1] Weng R M, Hsu X R, Kuo Y F. A 1.8-V high-precision compensated CMOS bandgap reference. IEEE Conference on Electron Devices and Solid-State Circuits, Dec 2005: 271

[2] Leung K N, Mok P K T, Leung C Y. A 2-V 23-μA 5.3-ppm/℃ curvature-compensated CMOS bandgap voltage reference. IEEE J Solid-State Circuits, 2003, 38: 561

[3] Lee I, Kim G, Kim W. Exponential curvature compensated BiCMOS bandgap references. IEEE J Solid-State Circuits, 1994, 29: 1396

[4] Rincon-Mora G A. Voltage references from diodes to precision high-order bandgap circuits. IEEE Press, Wiley Interscience, 2002

[5] Gray P, Hurst P J, Lewis S H, et al. Analysis and design of analog

Table 2. Summary of the performance of the proposed bandgap voltage reference.

Parameter	Proposed	Song *et al.*[7]	Lee *et al.*[3]	Rincon-Mora *et al.*[8]	Leung *et al.*[2]
Technology	0.6 μm BCD	CMOS	BiCMOS	BiCMOS	CMOS
Supply voltage (V)	2.2, 3.6, 5	±5	5	1.1 (min)	2, 3, 4
Supplu current (μA)	45 (max)	1200	74	15 (min)	23 (max)
V_{REF} (V)	1.2155±0.0006	1.192	1.264	0.595	1.14205 ± 0.00285
TC (ppm/℃)	5.3, 2.9, 3.5	25.6	8.9	<20	5.3, 6.1, 2.6
Line regulation (mV/V)	0.136 @ –20 ℃	—	—	408 ppm/V	±1.25 @ 0 ℃
	0.091 @ 30 ℃	—	—	408 ppm/V	±1.43 @ 27 ℃
	0.318 @ 120 ℃	—	—	408 ppm/V	±1.35 @ 100 ℃
PSRR (dB)	−85 @ 10 Hz	−55	−73	—	−47 @ 10 Hz
	−78 @ 1 kHz	−55	−73	—	−20 @ 1 kHz
	−37 @ 100 kHz	−55	−73	—	−10 @ 10 kHz
Chip area (mm^2)	0.062	2.258	0.044	0.223	0.057

integrated circuits. 4th ed. Wiley, 2001

[6] Chen J, Ni X, Mo B. A curvature compensated CMOS bandgap voltage reference for high precision applications. 7th International Conference on ASIC, 2007

[7] Song B S, Gray P R. A precision curvature compensated CMOS bandgap reference. IEEE J Solid-State Circuits, 1983, 18(6): 634

[8] Rincon-Mora G A, Allen P E. A 1.1-V current mode and piecewise linear curvature corrected bandgap reference. IEEE J Solid-State Circuits, 1998, 33: 1551

[9] Tsividis Y P. Accurate analysis of temperature effects in I_C–V_{BE} characteristics with application to bandgap reference sources. IEEE J Solid-State Circuits, 1980, 15: 1076

[10] Filanovsky I M, Chan Y F. BICMOS cascaded bandgap voltage reference. IEEE 39th Midwest Symposium on Circuits and Systems, 1996, 2: 943

[11] Buhanan D. Investigation of current-gain temperature dependence in silicon transistors. IEEE Trans Electron Devices, 1969, 16: 117

[12] Rein H M, Rohr H V, Wennekers P. A contribution to the current gain temperature dependence of bipolar transistors. Solid-Stare Electron, 1978: 439

[13] Dillard W C, Jaeger R C. The temperature dependence of the amplification factor of bipolar-junction transistors. IEEE Trans Electron Devices, 1987, 34: 139