

# Research on Design Method and Application of Bandgap Voltage Reference

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**Abstract.** With the progress and development of modern science and technology, more and more fields are inseparable from analog IC, and the demand for analog IC is increasing. From aerospace to mobile phones and televisions, analog IC are an indispensable part of these fields. In analog IC, one of the most common core components is a voltage reference that outputs a stable voltage that is not affected by temperature. However, the working environment of the voltage source will be different in different fields, so the design of voltage reference that meets the needs of their respective fields is one of the key research topics today, but there is still a lack of comparison and summary of the advantages and disadvantages of the different structures of the voltage reference used in different fields. Therefore, the research theme of this paper is to introduce the structure of voltage reference used in different fields, and compare and analyze the advantages and disadvantages of different structures, and discuss the development direction of future voltage reference on this basis.

**Keywords:** Bandgap voltage, integrated circuit, transistor.

## 1. Introduction

With the continuous development of integrated circuit technology, high-precision, high-speed, ultra-large-scale digital circuit design and manufacturing become easier and easier, some of the past by the analog circuit to achieve functional modules are gradually replaced by digital circuit modules. However, this does not mean that analog circuits will disappear. on the contrary, with the rapid development of digital circuit technology and the popularity of SOC(System on Chip) design technology, the importance of analog circuit will be further reflected. In analog integrated circuits, an important basic unit circuit, reference source, is widely used. This reference includes reference voltage source and reference current source. The reference source can be used either as a supply voltage or to provide an accurate reference voltage or current for other circuit modules. Moreover, its performance directly affects the performance of the whole circuit. For example, the bias current of the differential pair must be generated according to the reference, since it affects the voltage gain and noise of the circuit. In analog-to-digital converter (ADC) systems, voltage reference sources are also needed to determine the full range of its input or output. The change of reference with temperature and noise will seriously affect the performance of other modules in the circuit and the whole system. Therefore, it is not sensitive to changes in the external

environment such as process, supply voltage, and temperature, that is, the stability of the reference source is the main index in the design. If the stability of the reference source is not good, then the system performance is difficult to meet the design requirements.

A bandgap reference voltage source is a circuit that uses the physical characteristics of semiconductor materials to generate stable voltage, and it is the main part of bandgap reference circuit. It is based on the band structure and temperature characteristics of semiconductor materials to achieve high-precision reference voltage output. As a very important unit in analog and hybrid analog circuits, bandgap reference circuit has been paid more and more attention by scholars at home and abroad with the development of integrated circuits and the complication of SOC systems.

The bandgap reference circuit usually consists of a reference voltage source and an error amplifier. The main analysis of this paper is the structure of the bandgap voltage reference and the effect of different improvement schemes.

## 2. Design Principle of Reference Voltage Source

### 2.1. Negative temperature coefficient

The reference voltage source uses the bandgap property of semiconductor materials to generate a stable voltage independent of temperature variation, supply fluctuation and process. The research direction tends to get the temperature-independent voltage  $V_{ref}$ , that is, to find a positive correlation with temperature and a negative correlation with temperature voltage quantity.

The negative temperature coefficient is generally acted by the base-emitter forward voltage  $V_{BE}$  of the PN junction diode, and (1) is the expression of  $V_{BE}$

$$v_{be} = v_T \log_e \left( \frac{I_C}{I_S} \right) \quad (1)$$

ke the derivative of phi of (1)

$$\frac{\partial V_{be}}{\partial T} = \frac{\partial V_T}{\partial T} \log_e \left( \frac{I_C}{I_S} \right) - \frac{V_T}{I_S} \frac{\partial I_S}{\partial T} (I_C = \text{const}) \quad (2)$$

$$I_S = bT^{4+m} \exp \left( \frac{-E_g}{kT} \right) \quad (3)$$

Substituting (3) into (2) gives

$$\frac{\partial V_{be}}{\partial T} \approx \frac{V_{be} - (4+m)V_T - E_g/q}{T} \quad (4)$$

According to (4),  $V_{be}$  and have negative temperature coefficient (without considering the second-order effect).

$$\text{Assumptions} \quad V_{be} = 750mVT = 300^\circ K \quad (5)$$

By substituting the data in (5) into (4)

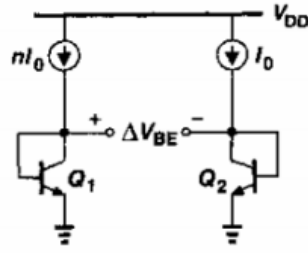
$$\frac{\partial V_{be}}{\partial T} = -1.5mV/^\circ K \quad (6)$$

According to (6), the negative temperature coefficient is  $-1.5mV/^\circ K$  at normal temperature and common voltage

### 2.2. Positive temperature coefficient

The positive temperature coefficient is generally used as the difference  $X$  of the forward voltage between the base and the emitter of two PN junction diodes under different current densities. Generally, there are two ways to change the current density by changing the flow current or changing the current density by changing the area of the PN junction.

First, the way of changing the current density by changing the flow current is introduced.



**Figure 1.** The current flowing through different PN nodes is the same.

Since Q1 and Q2 are exactly the same, it can be seen from Figure 1 that  $I_{S1} = I_{S2}$ ,  $A_{e1} = A_{e2}$ .  $X$  is expressed as (7) and  $V_{BE}$  is expressed as (8).

$$\Delta V_{be} = V_{be1} - V_{be2} \quad (7)$$

$$v_{be} = v_T \log_e \left( \frac{I_C}{I_S} \right) \quad (8)$$

Substituting (8) into (7) yields (9).

$$\Delta V_{be} = V_T \log_e n \quad (9)$$

$$V_T = \frac{kT}{q} \quad (10)$$

Then substituting (10) into (9) gives

$$\frac{\partial V_{be}}{\partial T} = \frac{k}{q} \log_e(nm) \quad (11)$$

It can be concluded from (11) that the base-emitter forward voltage difference  $\Delta V_{BE}$  of two PN junction diodes under different current densities has a positive temperature coefficient, where  $k/q$  is a constant and is about  $0.087 \text{ mV}/^\circ\text{K}$ .

As with the above derivation, the final result is simply to add the area ratio 'm' to  $\log_e(n)$  to obtain (12).

$$\frac{\partial V_{be}}{\partial T} = \frac{k}{q} \log_e(nm) \quad (12)$$

### 2.3. Band gap reference

Finally, the bandgap reference is used to realize the superposition of the two, so as to realize the output voltage not affected by temperature, so it can be assumed that (13)

$$V_{ref} = K_1 V_1 + K_2 V_2 \quad (13)$$

Combined with the previous derivation, (13) can be changed into (14).

$$V_{ref} = \alpha_1 V_{be} + \alpha_2 V_T \log_e n \quad (14)$$

$$\frac{\partial V_{be}}{\partial T} = -1.5 \text{ mV}/^\circ\text{K}, \frac{\partial V_T}{\partial T} = \frac{k}{q} = 0.087 \text{ mV}/^\circ\text{K} \quad (15)$$

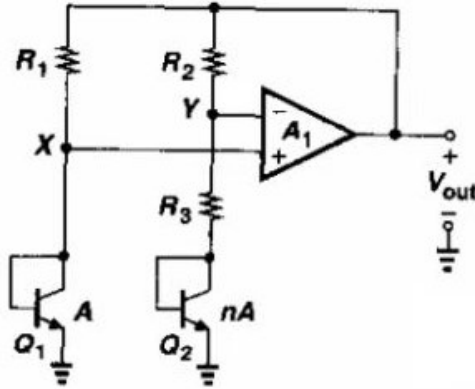
Let  $\alpha_1 = 1$ ,  $\alpha_2 = \alpha$  in (14) and substitute the value in (15) to obtain (16).

$$\frac{\partial V_{ref}}{\partial T} = -1.5 + 0.087\alpha \log_e n \quad (16)$$

So it follows that  $\alpha \log_e n \approx 17.2$  holds if and only if  $\alpha \log_e n \approx 17.2$ , in which case  $V_{ref}$  equals 0, and the output voltage is not affected by temperature. In general,  $V_{be}$  and the size of  $V_T$  are relatively fixed, as shown in (16), so the value of  $V_{ref}$  is generally 1.25V. Part of the optimization of the circuit structure is also devoted to improving the problem that the output voltage is quite stable.

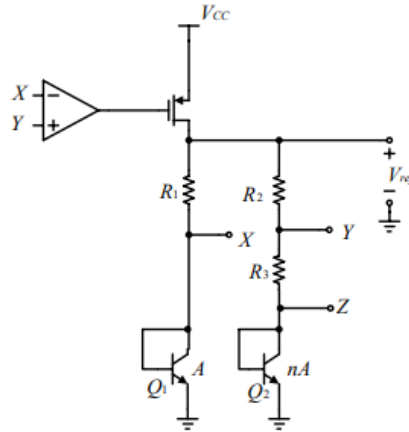
### 3. Bandgap voltage reference circuit structure principle

#### 3.1. Basic circuit



**Figure 2.** A common basic circuit [1].

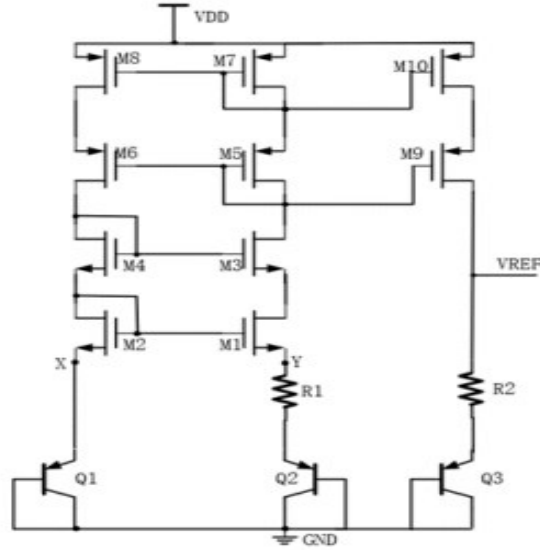
It can be seen from Figure 2 that the current of  $R_3$  is given by  $\frac{V_{BE2}}{R_3}$ . Since  $R_1$  is equal to  $R_2$ , the currents flowing through them are also the same, so the voltage of  $R_1$  is equal to  $V_{out} = \frac{R_1 \Delta V_{BE}}{R_3} + V_{BE1}$ . So the output voltage has  $V_{out} = \frac{R_1 \Delta V_{BE}}{R_3} + V_{BE1}$ . Therefore, after satisfying the structure premise  $R_1 = R_2$ , if the size of  $V_{out}$  is to be designed, it can be regulated by setting the ratio of  $R_1$  and  $R_3$ , and the power consumption of the whole circuit is determined by  $R_3$ .



**Figure 3.** Another common basic circuit.

Figure 3 is another common bandgap reference voltage source structure, and the derivation process is exactly the same as that in Figure 1.

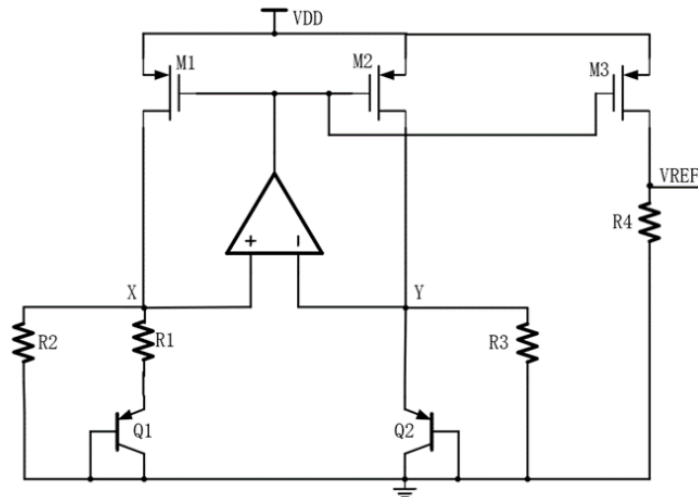
### 3.2. The current mirror structure is used instead of the operational amplifier



**Figure 4.** The current mirror structure is used to replace the operational amplifier circuit structure diagram.

As shown in FIG. 4, the structure replaces the opamp with a current mirror structure based on the basic structure and adds a resistor at the output to output the required voltage. Compared with the case of using an op-amp in this structure[2], the structure can directly output positive temperature coefficient current, but using the current mirror structure leads to a decrease in accuracy and is greatly affected by the transistor parameters

### 3.3. Superimposed current structure



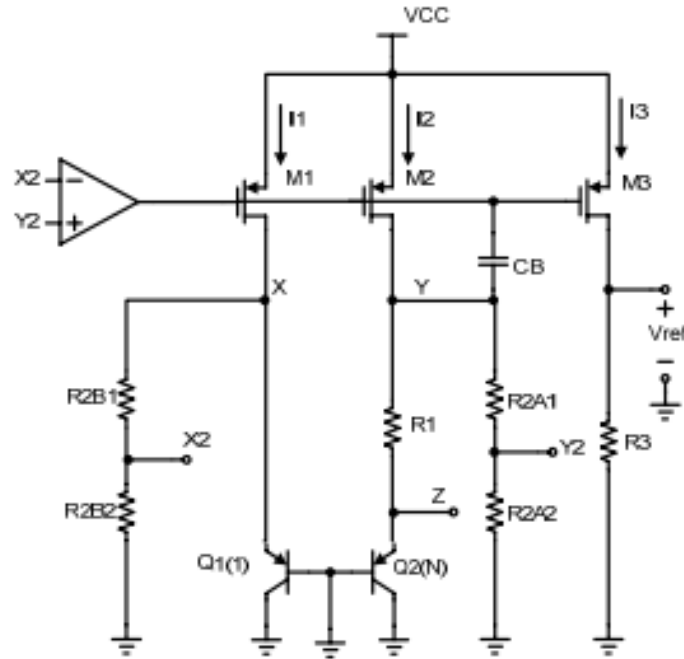
**Figure 5.** Superimposed current structure( $R_2=R_3$  in the circuit,  $M_1$  is exactly the same as  $M_2$ ).

This structure is quite different from the above structure. The current with positive and negative temperature coefficients are superimposed to realize the output bandgap reference voltage, and the current flowing through  $R_1$  is  $\frac{\Delta V_{BE}}{R_1}$ [3].

Since M1 is exactly the same as M2, point X is exactly the same as point Y, and since  $R_2=R_3$ , the current flowing through R2 is equal to the current flowing through R3, in figure 5. Therefore, the current flowing through M2 can be obtained by adding  $\frac{\Delta V_{BE}}{R_1}$  and  $\frac{V_{BE2}}{R_3}$ .

Therefore, it can be concluded that  $V_{REF}$  is  $\frac{R_4}{R_3} (\frac{R_3 \Delta V_{BE}}{R_1} + V_{BE2})$ . As can be seen from it, the advantage of this circuit structure compared with the traditional structure of superposition plus voltage is that the output voltage  $V_{REF}$  can be adjusted through  $R_4$  to be greater than or less than 1.2V, but the maximum value cannot be greater than  $V_{DD}-V_{DS}$

### 3.4. Further improvement of the circuit structure for superimposing current



**Figure 6.** Further improvement of the superposition current circuit structure.

From the analysis of figure. 6 and the previous circuit diagram,  $V_{REF}$  can be obtained as  $\frac{R_3}{R_2} (\frac{R_2 \Delta V_{BE}}{R_1} + V_{BE2})$ .

Since the voltage drop on  $R_{2B1}$  and  $R_{2B2}$  is  $V_{BE1}$ , the voltage to ground of  $X_2$  can be obtained as  $\frac{R_{2B2}}{R_{2B1}+R_{2B2}} \times V_{BE1}$  that the lowest operating voltage is  $\frac{R_{2B2}}{R_{2B1}+R_{2B2}} \times V_{BE1} + |V_{thp}| + 2|V_{DS(sat)}|$

It can be concluded that the advantage of this improved structure is that the power supply voltage can be reduced by properly allocating the size of  $R_{2A2}$  and  $R_{2B2}$

## 4. Advantages of Bandgap Voltage Reference

Through the above derivation, the advantages of bandgap voltage reference can be summarized. Firstly, the bandgap reference through a specific design has temperature stability and is able to generate a stable reference voltage at different temperatures. Second, the bandgap reference voltage source has a strong anti-interference ability to power fluctuations but also has a high precision, and can achieve a high precision reference voltage output usually in a few millivolts or less. Finally, the band-gap reference voltage source also has the characteristics of fast response, and the output voltage can be quickly adjusted to the dynamic input signal.

## **5. The Characteristics of Bandgap Voltage Reference With Different Structure Improvement and its Application In Different Fields**

On the basis of the above common variant bandgap voltage reference structure, many researchers have proposed innovative structures with their own advantages. On the basis of the above superposition current structure, additional transistors are connected in series to realize high-order compensation, which reduces the problem of excessive temperature drift and instability of the traditional bandgap voltage reference [4]. By designing part of the MOS transistors into diode link mode to provide bias voltage, and then making part of the MOS transistors work in the deep linear region as resistors, the positive temperature coefficient voltage is obtained, so that the whole circuit no longer needs resistance, and the error and chip area caused by resistance manufacturing process are reduced [5]. Using the second-order curvature compensation and the structure with temperature drift adjustment [6], only a set of resistors can be used to achieve the adjustment of temperature drift characteristics, which significantly improves the accuracy of the reference voltage and improves the temperature coefficient of the voltage source. There is also a lot of research on improving the accuracy of bandgap reference, For example, by adding a P-type reference resistor with positive temperature coefficient to improve the structure to achieve the effect of second-order temperature compensation [7], and by using a pull-up MOSFET in series with L pull-down MOSFETs [8] to output positive temperature coefficient current, the power consumption is reduced and the accuracy of the bandgap voltage reference is improved. In terms of the power rejection ratio of the bandgap reference voltage source, some people have proposed an improved scheme [9], and designed a circuit structure with low temperature coefficient and high voltage rejection ratio effect. Because of the rapid development of various fields, the demand for different types of chips is also growing rapidly. For chips with high radiation resistance required in the field of spacecraft and satellites, corresponding bandgap voltage reference sources have been designed to resist total dose radiation[10][11]. In the traditional structure, the total dose of radiation will lead to charge entering into the oxide, which will reduce the DC gain and increase the leakage current and base current, resulting in dramatic changes in the characteristics of VBE. Eventually, the positive temperature coefficient becomes larger and the negative temperature coefficient becomes smaller, which cannot be offset by the preset full addition, so that the original set VREF temperature coefficient changes, and the preset effect cannot be achieved. In this paper, the diode link mode is used to generate positive and negative temperature coefficients instead of transistors, because the diode can generate positive and negative temperature coefficients while the base region is less affected by the charge in the oxide layer. There is also a demand for bandgap reference voltage source in the electronic integrated chips of automobiles [12]. According to this paper [13], the circuit structure that meets the working environment conditions of automobiles is proposed. The internal voltage generator provides stable power for the error amplifier, and then the output voltage is detected and controlled by the error amplifier. As can be seen from the above literature, the application range of bandgap reference voltage sources is constantly expanding, and the current research direction is mostly to meet the needs of a certain field's use environment while improving circuit accuracy or stability. This is the future direction of bandgap reference voltage sources.

## **6. Future Research Directions For Bandgap Voltage Reference Sources**

More and more fields begin to put forward the demand for high-performance analog integrated circuits, reference voltage as one of the important components, will be required by more and more complex scenes. Therefore, in the future, the key research direction of bandgap voltage reference will be more inclined to broaden the applicable environment of the voltage source, such as ensuring high precision and controllable temperature coefficient under the power supply voltage in more extreme environments, and adjusting according to the special circumstances of different fields. Circuit design according to different needs is the future research and development direction of bandgap reference voltage source.

This paper presents the basic principles of bandgap voltage reference and illustrates the advantages of these extended circuits from the basic circuit to various representative extended circuits compared to the original circuit. At the same time, several improvement directions and corresponding examples of the bandgap voltage reference structure are introduced, such as more compensation means, lower power

consumption and replacing the existing structure with another structure to achieve some goals. Several kinds of chips used in specific fields are introduced, and their principles and advantages are briefly introduced.

Therefore, through the above discussion and the analysis of the literature, it can be concluded that there are still many challenges in the future bandgap voltage reference, such as how to ensure the normal operation of the circuit in high temperature or low temperature environment, how to improve the temperature coefficient of the circuit to improve the output current accuracy based on the previous circuit, how to reduce the requirements for the process, how to control the power consumption according to the demand, and how to reduce the temperature coefficient of the circuit. Cost, voltage rejection ratio and other indicators. These are the challenges that future bandgap benchmark circuits will encounter in practical applications in various neighborhoods.

For these challenges, some researchers have begun to study them by adding first-order and second-order temperature compensation circuits to reduce the temperature coefficient and improve the output voltage accuracy [2]. In addition, the use of special resistors to achieve temperature compensation in low temperature environment to achieve low temperature coefficient voltage output [13] to improve the current situation that many circuits are demanding on temperature. These examples can prove that the current research direction of bandgap voltage reference is to improve the output accuracy and broaden the applicable environment. Of course, to do these two things is not only to work on the temperature and aspects, in order to output a variety of voltage values, better adapt to the situation that different parts of the chip need a variety of different sizes of voltage at the same time, there are also special studies [14].

In conclusion, now almost all industries are inseparable from the integrated circuit, and as an important part of the integrated circuit, the bandgap benchmark circuit part is also very important. In order to comply with such a development trend, the bandgap reference voltage source has also begun to change and improve. By summarizing and comparing the advantages and disadvantages of the old structure and then improving the structure on this basis, the effect is achieved by adding circuit structures such as compensation circuits. This will also be the development trend of bandgap benchmark circuits in the future, through the improvement of the structure to adapt to the different needs in the market now.

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