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Semester Project – Bandgap Reference Voltage

ESPLAB - Electronic and Signal Processing Laboratory

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Abstract

ABSTRACT

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1 Principle & Specifications

Voltage references have always been an essential component of any system and consequently an important topic to explore. The last decades thrust toward higher and even total system integration has required all designers to be knowledgeable of this particular topic due to its mixed-signal implications (output impedance, temperature coefficient, etc...)

A general-use (ideal) voltage reference is a circuit used to generate a fixed voltage, V_{ref}, that is independent of the power supply voltage VDD (where $V_{ref} < VDD$), temperature, and process variations. In other words, the ideal reference voltage is independent of PVT. In some cases, we want to design a reference that varies with temperature. For example, if V_{ref} increases with temperature, Fig. 1.2, we say that the reference voltage is proportional to absolute temperature or **PTAT**. If the reference voltage decreases with increasing temperature, Fig. 1.1, the reference is said to be complementary to absolute temperature or **CTAT**.

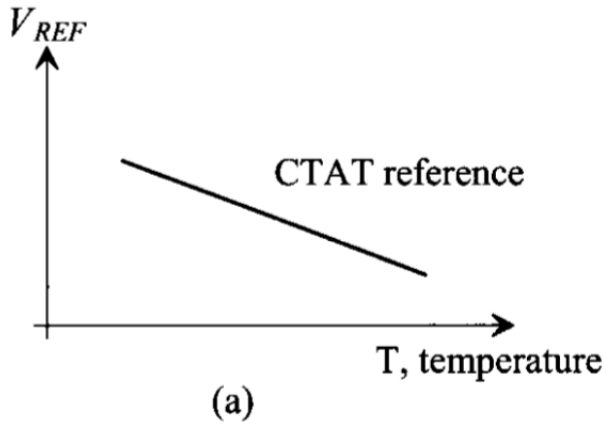

FIGURE 1.1 – CTAT Voltage Evolution

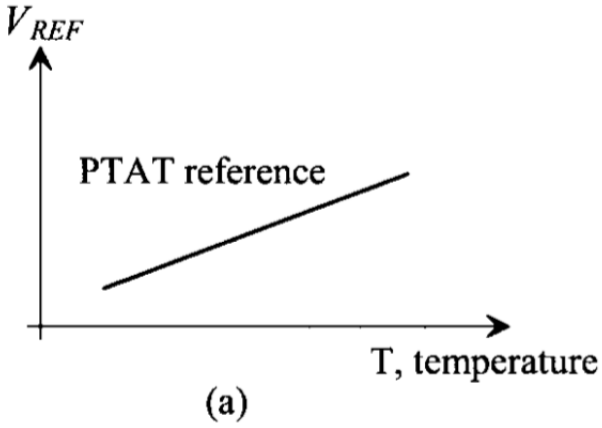

FIGURE 1.2 – PTAT Voltage Evolution

The **PTAT** and **CTAT** references can be used to design a voltage reference that changes very little with temperature called a bandgap reference. We only need to sum the two voltages with the correct coefficient K (Fig. 1.3).

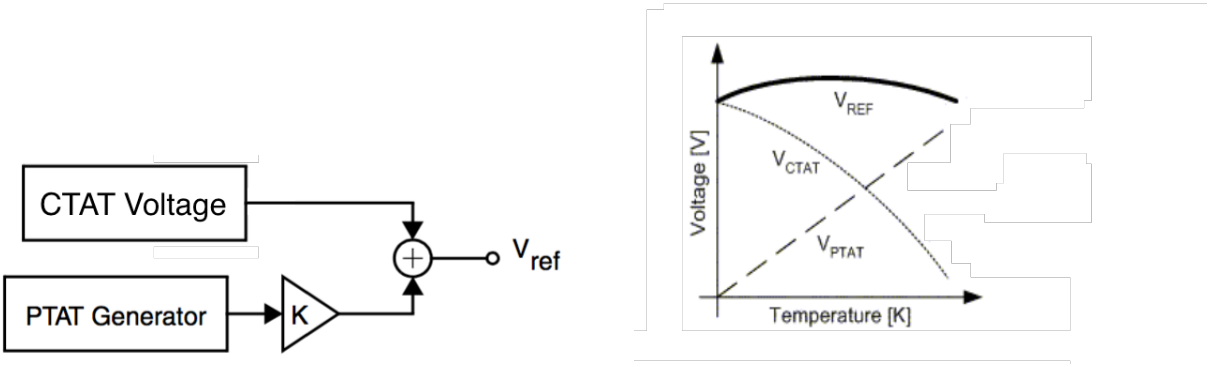

Figure 1.3 – General Bandgap Voltage Principle

Now, we need to find the component, or a characteristic that has a PTAT or CTAT behaviour. We are going to use the usual componenent, Bipolar and MOS transistor. In one hand, we can notice that the temperature coefficient of (evolution with respect to Temperature) V_{BE} is negative, as well as the V_{GS} of a MOS transitor. In the other hand, we can observe that two bipolar or MOS transistor working at a unequal current densities create a voltage that is proportionnal to $U_T = \frac{kT}{q}$ therefore PTAT voltage (Positive Temperature Coefficient - TC).

The bandgap voltage reference will be used in different block, and for applications with low power consumption. The design will then take into account some specifications related to these applications. We can resume the main specifications of this project in the next table :

	Typ	Maximum	Minimum
Current Consumption	1 μA	3 μA	—
Power Supply Voltage	1.8 V	2 V	1.5 V
Technology	UMC L180UMC L180		

Table 1.1 – Voltage Reference Specifications

2 Generate a CTAT Voltage

2.1 Evolution of V_{BE} with respect to temperature

The base-emmiter voltage of a bipolar transistors or, more generally, the forward voltage of a pn-junction diode show a negative TC. For a bipolar device such as represented in the Fig. 2.1

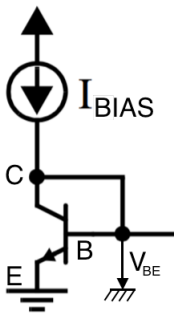

FIGURE 2.1 – Base-emitter Voltage Context

$$V_{BE} = \frac{k_B T}{q} \cdot ln\left(\frac{I_C}{I_S}\right) \tag{2.1}$$

With I_S, the saturation current which depend on the temperature through different characteristic (n_i, μ_0) that depend differently of temperature. In a first calculation, we suppose that the collector current I_C is independent of the temperature. After calculation (details on Appendix **??**) we obtain :

$$\frac{\partial V_{BE}}{\partial T} = \frac{V_{BE} - (4+m)U_T - E_g/q}{T} \tag{2.2}$$

Where $m/approx - 3/2$ a process parameter, $E_g/approx 1.12eV$ the bandgap energy of silicon, $U_T = \frac{kT}{q}$ the thermal voltage. The equation 2.2, reveal the dependence of the TC of V_{BE} to the magnitude of V_{BE} itself. We then fix $V_B E \approx 700mV$, $T \approx 300K$ and we obtain $\frac{\partial V_{BE}}{\partial T} \approx -1.2mV/K$. In fact, in this part we limit our temperature analysis to the dependence to the first order of temperature which create a second order temperature dependence.

2.2 Bipolar Implementation in CMOS process

The implementation of a bipolar transitor in a CMOS process used here process a lateral bipolar transistor which can be better controled and processed with a much better accuracy than the vertical bipolar. In fact, during the process, the depth of oxydation in the silicon is controlled with much more difficulty whereas the oxydation of a specific area is much more controled and processed with a better accuracy. We then use a lateral transistor, processed and layouted as in the Fig 2.2 :

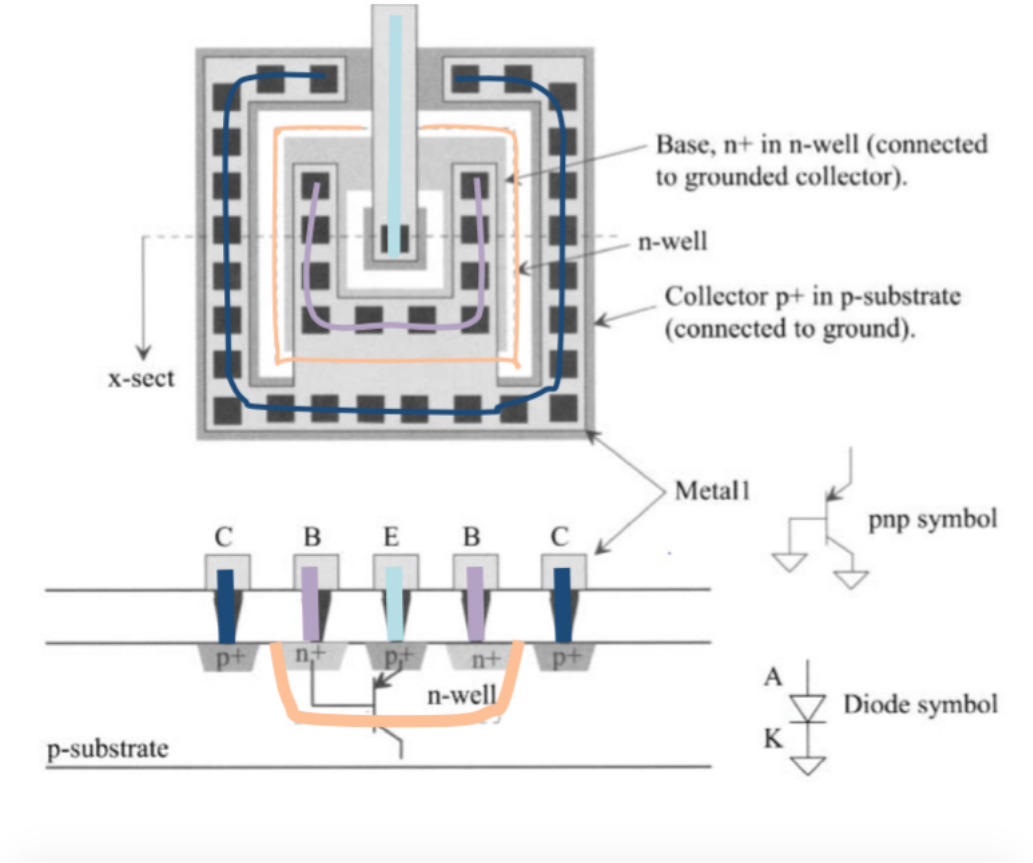

Figure 2.2 – Layout of PNP Bipolar Transitor

3 Generate a PTAT Voltage

3.1 Using Base-emitter Voltage

As said in the first chapter, we are going to use two bipolar transistor in two different current densities, and then the difference between their base-emitter voltage produce a voltage which is proportionnal to the thermal voltage, we then have a PTAT voltage.

We are going to use two branches with the same current I, and in one branch we are going to use n identical bipolar transitor and one bipolar transistor in the other branch ($I_{S2} = nI_S$ and $I_{S1} = I_S$).

$$\Delta V_{BE} = V_{BE1} - V_{BE2} \tag{3.1}$$

$$= U_T ln\left(\frac{I_0}{I_{S1}}\right) - U_T ln\left(\frac{I_0}{I_{S2}}\right) \tag{3.2}$$

$$= \frac{kT}{q} \cdot ln(n) \tag{3.3}$$

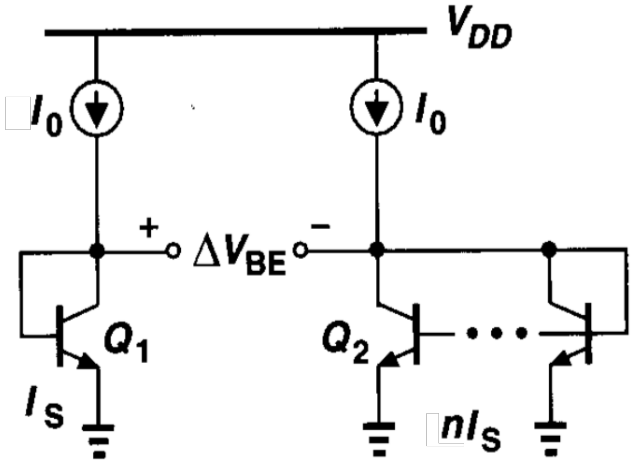

FIGURE 3.1 – Generate a PTAT Voltage

The precedent structure manipulate a differential voltage, the final idea is to add this voltage to a CTAT voltage which is not possible in a complete structure, so instead of generating a PTAT differential voltage, we generate a PTAT current which we can easily copy in another branch.

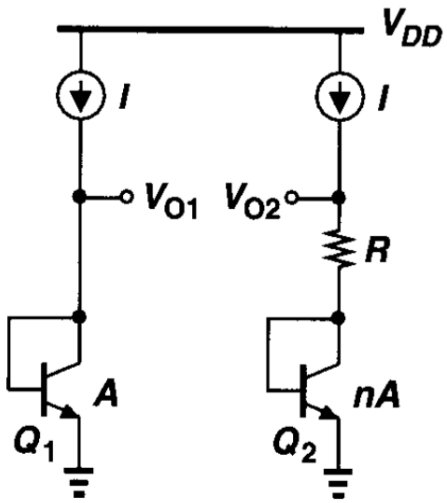

Figure 3.2 – Generate a PTAT Current

In this structure, we need also use a mechanism that will force $V_{O1} = V_{O2}$, we will use a operational amplifier with a high gain to force the two voltages to be equal.

$$V_{O1} = V_{O2} \tag{3.4}$$
$$V_{BE1} = RI + V_{BE2} \tag{3.5}$$
$$I = \frac{\Delta V_{BE}}{R} \tag{3.6}$$
$$= \frac{\frac{kT}{q} \cdot ln(n)}{R} \tag{3.7}$$

We obtain finally a PTAT current proportional to the thermal voltage that is easier to sum with a CTAT current or Voltage. Moreover we have two parameter n and R, that we can fix to cancel the negative temperature coefficient.

3.2 Using Gate-source Voltage

We use two transistor M1 and M2, which will operate in weak inversion with two different current densities. This region of operation have quasi the same way of variation than the bipolar transistor, whith a exponential dependence of the drain current with respect to the gate-source voltage.

$$I_{DS} = I_{SPECs} \cdot \frac{W}{L} \cdot exp\left(q\frac{V_{gs} - V_t}{nkT}\right) \tag{3.8}$$
$$I_{SPECs} = 2n\mu_n C_{ox} U_t^2 \tag{3.9}$$

In the same way, we use an Opamp to ensure that the two voltages V_A V_B are equal. We use the same current in the two branches, and we size the transistor M2 m times larger than M1, we then have :

$$V_{GS1} = nU_T \cdot ln\left(\frac{I_{DS1} \cdot L_1}{I_{SPECs} \cdot W_1} + V_{T0}\right) \tag{3.10}$$

$$V_{GS2} = nU_T \cdot ln\left(\frac{I_{DS2} \cdot L_2}{I_{SPECs} \cdot W_2} + V_{T0}\right) \tag{3.11}$$

$$\frac{W_2}{L_2} = m \cdot \frac{W_1}{L_1} \tag{3.12}$$

In the same logic we obtain a current I_{R1} which is proportional to ΔV_{GS}, in fact the final theoritical expression of $I_{R1} = \frac{\Delta V_{GS}}{R_1}$ with :

$$\Delta V_{GS} = \ n \ \frac{kT}{q} ln(m) \tag{3.13}$$

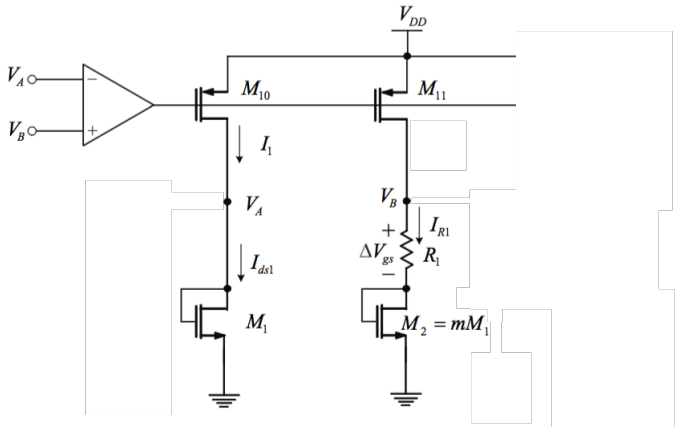

Figure 3.3 – Generate a PTAT Current with MOS transistor

The final result is very similar to the bipolar "version", except that for the MOS version, ΔV_{GS} is proportionnal to the slope factor, except that this parameter is dependent of the temperature, the variation can be neglected for the dependence of the first order of temperature.

4 Bandgap Voltage

4.1 Current Source - Beta-Multiplier

As we are limited to 3 μA in current consumption, we are going to limit the current consumption in the current-source to the minimum. We decide then to produce a current of 100 nA that we are going to mirror in the different branches to generate a PTAT and a CTAT voltage. To generate this current, we are going the structure in the Fig 4.1 :

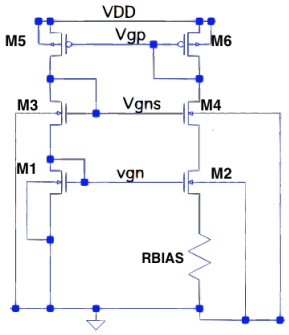

FIGURE 4.1 – Beta-Multiplier Current Source

For such low current, we use the two transistor M1 and M2 in weak inversion, and to obtain a good current mirror with respect to mismatch and have I_{ref} quasi equal to I_{out} we put the transistor M3 and M4 in strong inversion.

$$I_{out} = I_{spec} \cdot exp\left(\frac{V_G - nV_S - V_{T0}}{nU_T}\right) \tag{4.1}$$

$W_1 = 4\ \mu m$	$L_1 = 180\ nm$
$W_2 = 16\ \mu m$	$L_2 = 180\ nm$
$W_3 = W_4 = 5\ \mu m$	$L_3 = L_4 = 250\ nm$
$W_5 = W_6 = 1\ \mu m$	$L_5 = L_6 = 300\ nm$

TABLE 4.1 – Beta-Multiplier transitor dimension

If we apply this equation to the transitor M1 and M2, with M2 k times larger than M1, we have a simple equation :

$$I_{out} = I_{ref} = \frac{U_T \cdot ln(k)}{R_S} \tag{4.2}$$

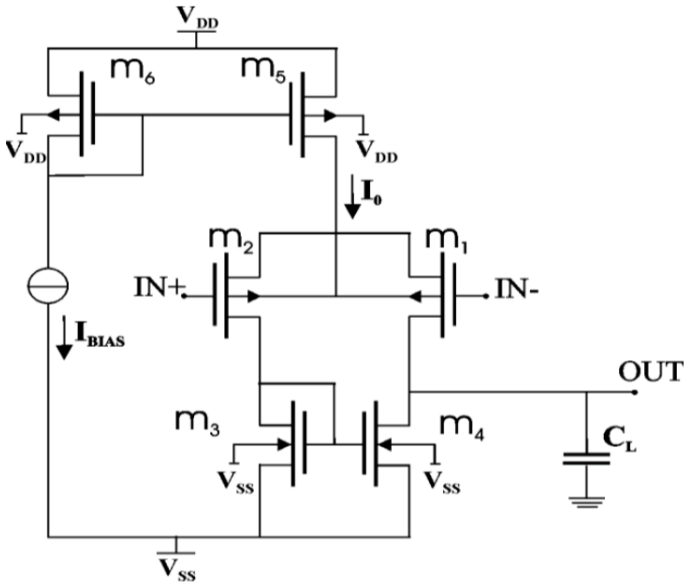

Figure 4.2 – OTA with PMOS differential pair

$W_1 = W_2 = \mu m$	$L_1 = L_2 = \mu m$
$W_3 = W_4 = \mu m$	$L_3 = L_4 = \mu m$
$W_5 = \mu m$	$L_5 = \mu m$

Table 4.2 – OTA transitor dimension

4.2 Single Stage OTA

4.3 Overall circuits

4.3.1 Bandgap Voltage Reference

4.3.2 Sub-1V Bandgap Current and Voltage Reference

5 Results after Simulation

5.1 Temperature Dependence

5.2 Dependence to VDD - PSRR

5.3 Simulation Post route

Conclusion

Annexes

A Evolution of V_{BE} with respect to temperature

The details of the calculation of the dependence of V_{BE} to temperature. We fisrt devellop the temperature dependence :

$$V_{BE} = \frac{k_B T}{q} \cdot ln\left(\frac{I_C}{I_S}\right) \tag{A.1}$$

$$I_S \ \alpha \ \mu \ kT \ n_i^2 \tag{A.2}$$

$$\mu \ \alpha \ \mu_0 \ T^m \tag{A.3}$$

$$n_i^2 \ \alpha \ T^3 \cdot exp\left(\frac{E_g}{kT}\right) \tag{A.4}$$

With μ the mobility of the carriers, n_i the intrinsic carrier concentration of silicon and $E_g \approx 1.12eV$ the bandgap energy of silicon.

We introduce a parameter b, which is a proprtionnality factor :

$$I_S = bT^{4+m} \cdot exp\left(\frac{E_g}{kT}\right) \tag{A.5}$$

Once we have devellop the expression with respect with T, we start to derivate the expression :

$$\frac{\partial V_{BE}}{\partial T} = \frac{\partial U_T}{\partial T} \cdot ln\left(\frac{I_C}{I_S}\right) + \frac{\partial I_S}{\partial T} \cdot \frac{U_T}{I_S} \tag{A.6}$$

$$\frac{\partial I_S}{\partial T} = b(4+m)T^{3+m} \cdot exp\left(\frac{E_g}{kT}\right) + bT^{4+m}\left(exp\left(\frac{E_g}{kT}\right)\right) \cdot \frac{E_g}{kT^2} \tag{A.7}$$

$$\frac{U_T}{I_S}\frac{\partial I_S}{\partial T} = (4+m)\frac{U_T}{T} + \frac{E_g}{kT^2} \cdot U_T \tag{A.8}$$

We obtain finally :

$$\frac{\partial V_{BE}}{\partial T} = \frac{U_T}{T} ln\left(\frac{I_C}{I_S}\right) - (4+m)\frac{U_T}{T} - \frac{E_g}{kT^2} \cdot U_T \tag{A.9}$$

$$\frac{\partial V_{BE}}{\partial T} = \frac{V_{BE} - (4+m)U_T - E_g/q}{T} \tag{A.10}$$

B ANNEXE B

C ANNEXE C