A Low-voltage, Low-power 1.03V Voltage Reference For Implantable Medical Devices

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***Abstract*— In this work an integrated low supply voltage, low-power 1.03V voltage reference for implantable medical devices is presented. The circuit was designed, simulated and fabricated in a 0.6µm technology. Simulated and measured results show that output voltage varies less than 3mV while varying supply voltages from 1.7V to 5V, and has a standard deviation of 13mV between different measured chips. To reduce the power consumption the output is buffered and the bandgap circuit is periodically turned on and off, resulting in a total current consumption of less than 200nA, which fits regular requirements of medical devices.**

***Index Terms*—Low power, voltage reference, CMOS.**

I. INTRODUCTION

In the last few years, implantable medical devices are being implemented for the treatment of a growing number of pathologies [1][2]. Microelectronics is an essential tool for these new treatments as these new implantable medical devices are complex electronic circuits performing several tasks including sensing, control, and stimulation to re-establish different body functions of the patient. Integrated voltage references are an integral part of these devices, since accurate voltage references enable precise delivery of voltage stimuli and accurate detection of biological signal (e.g. using an AD converter).

Several voltage references are designed to minimize its variation with temperature [3][4], but in the case of implantable medical applications, the temperature is fixed by the human body varying only a handful of degrees around 37º Celsius. On the other hand, implantable medical devices must work for a wide range of supply voltages, varying from 4.2V (completely charged lithium medical grade rechargeable battery) to less than 2V (end of life condition for a pacemaker lithium-iodine medical grade battery) [5][6].

Like all circuits for implantable medical devices, power consumption must be minimum to extend battery life. Furthermore, with very low power consumption multiple voltage references can be included, minimizing the effect of one part of the chip on another.

II. VOLTAGE REFERENCE DESING

In order to develop the specifications for this circuit, a voltage reference to be included in different ASICs (application-specific integrated circuits) for different medical devices was proposed. Therefore, supply voltages for the designed circuit can have a large variation since not all applications are powered with the same batteries. On the other hand, in implantable devices, temperature variations are very small during normal operation; thus in this design a low temperature variation coefficient is not crucial. As this voltage reference was designed to be a part of a larger circuit, it was decided that no trimming was going to be used. The reference voltage should not vary more than 3% between different samples, and the selected nominal value was 1.03V. Current consumption must be kept to a minimum, and the design target was to consume up to 250nA.

In Table 1 the complete specifications of the designed voltage reference generator are presented.

TABLE 1: VOLTAGE REFERENCE SPECIFICATIONS

	Specifications
Output Voltage	1.03V ± 3%
Voltage Supply	1.8V – 5V
Temperature Range	20º - 50º
Temperature Coefficient	<1mV/ºC
Current Consumption	<250nA

To implement the voltage reference generator, the bandgap circuit of figure 1 was selected [7]. This particular configuration was used because it reduces the minimum supply voltage needed while improving the current mirrors performance. Transistors M1 and M2 together with the transconductor guarantee that the currents through both branches are equal. Resistors R1 and R3 are equal and are “L” times larger than resistor R2. Both bipolar transistors are connected as diodes, and b2 is made out of “K” unitary transistors while b1 is only one. Transistor st1, st2 and st3 are the start-up circuit, and the MON transistor can be used to turn off the bandgap circuit.

The output voltage and current through each branch can be determined as:

$$V_{REF} = n\phi_T \left[Ln\left(\frac{I}{KI_S}\right) + (L+1)Ln(K) \right] \quad (1)$$

and

$$I = \frac{n\phi_T Ln(K)}{R2} \quad (2)$$

Where ϕ_T is the thermal voltage (26.7mV for 37ºC), I_S is the reverse saturation current (approximately 0.11fA for the unitary bipolar transistor in the selected technology), n=1 for bipolar devices and I is the current through each branch.

For this bandgap, the following values were selected for the design parameters: L=8, K=8 and R2=156kΩ. These parameter values determine I = 356nA and VREF = 1.029V. The designed transconductor consumes 80nA and the start-up transistors less than 38nA during normal operation. Total current consumption of the bandgap circuit is therefore 830nA. Figure 2 shows the transistor level implementation of the transconductor. A current source of 40nA must be connected to POL, obtained from a current source like [8] for example. Transistors MN1 and MN2 can be used to turn off the OTA.

Simulations show that all specifications were within the expected range except current consumption. Also the maximum allowed load for the circuit was too low for the intended application. To solve both problems, the bandgap circuit is periodically turned on and off while a Miller amplifier buffer circuit maintains the output value when the bandgap circuit is turned off. In most integrated circuits for medical applications, a low frequency clock is available (used in a small microprocessor, an AD converter or for communication purposes for instance). For this design it was assumed that a 256Hz clock signal was available (in general, if a higher frequency clock is available, it can be easily divided. E.g. the 256Hz can be obtained easily from the standard 32.768kHz). A small and simple logic generates two different signals ONB, ONC and their complements. Both signals have the same frequency but ONB has a longer duty cycle. The logic first turns on the bandgap and buffer circuits, and only after these circuits have been on for at least 2ms and have already stabilized, a transmission gate is closed and the output capacitor voltage is charged. Figure 3 shows the complete diagram of the system. The output capacitor can be internal or external depending on the application. This capacitor does not need to be of an extremely high voltage, as the second miller buffer is the one connected to the load. For this design, a 4Hz frequency was selected and the output capacitor was implemented externally for measurement purposes.

Duty cycles of 1/8 and 1/16 were used for the Bandgap and the transmission gate, respectively. Using this architecture, current consumption was reduced to 200nA, which complies with the original specifications.

The output buffer was implemented using a low offset nmos input Miller amplifier. Input transistors must be large (W=100um and L=6um) to minimize the offset caused by mismatch, as this offset modifies directly the output of the voltage reference. Figure 4 shows the schematic with all transistor's sizes, while figure 5 the complete layout of the circuit. Total area of the design is 0.11mm2 excluding the output capacitor.

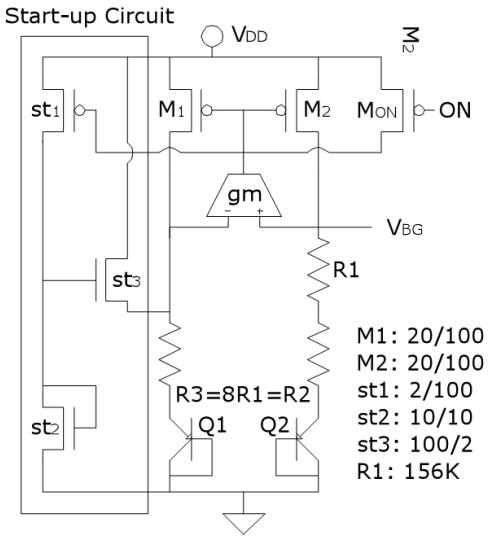

Fig 1: Bandgap circuit schematic. On the left, the start-up circuit. VBG is the output reference value. All transistor sizes are in micrometers.

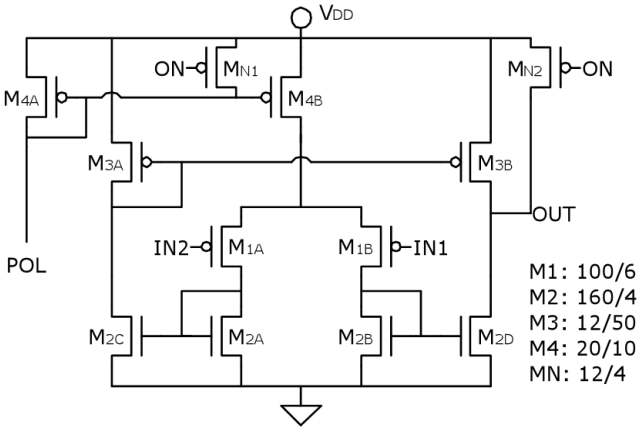

Fig. 2: Bandgap OTA schematic. Note the large size of the input transistors, to reduce the offset due to mismatch. All transistor sizes are in micrometers.

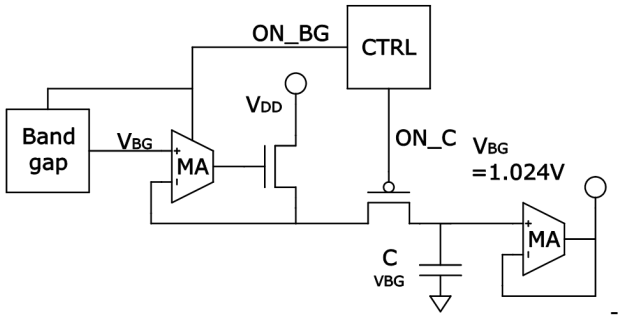

Fig 3: Complete voltage reference circuit schematic. C_{VBG} is an external capacitor for measurements purposes.

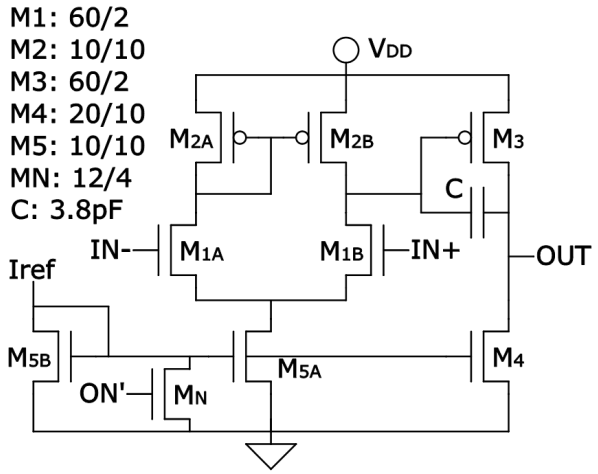

Fig 4: Miller amplifier schematic.

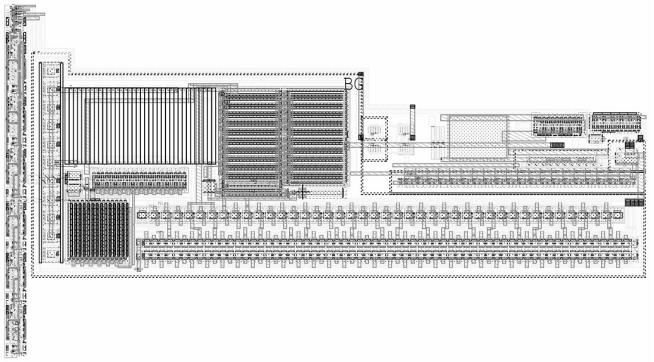

Fig 5: Bandgap circuit layout, on the left the logic circuit and the bipolar transistors, in the top centre the three resistors and at the bottom the buffer input pair.

III. VOLTAGE REFERENCE SIMULATIONS

In this section, several simulations (BSim 3v3 was used) of the designed voltage reference are presented. In figure 6 the reference voltage circuit's output is shown for different supply voltages. It can be seen that the reference voltage varies less than 1mV for all expected supply values. A temperature analysis reveals that the voltage reference varies about 0.6mV/ºC. The circuit was simulated for different models (typical model, TM; worst slow, WS; worst power, WP) and table 2 shows its output values for different models and different supply voltages. The output is between 1.020V and 1.041V at 2.8V, which represents a 1% variation from the expected value. The start-up of the whole circuit is shown in figure 7 with a 2.8V supply voltage. During the first cycles, the output measurement capacitor of 1µF is being charged until it stabilizes. Stabilization time was less than 4 seconds for all models and different power supplies with the 1µF capacitor. Stabilization times increases for lower power supply values but decreases for lower capacior's values. A 1µF capacitor was used for reported values as the maximum reasonable value of an external capacitor and also to simplify measurements.

The mean current consumption of the whole circuit was in all simulated cases less than 200nA.

TABLE 2: VOLTAGE REFERENCE OUTPUT VALUE FOR DIFFERENT SUPPLY VOLTAGES AND DIFFERENT SIMULATIONS MODELS.

VDD (V) \Model	TM	WS	WP
2.0	1.0283	1.0410	1.0200
2.4	1.0285	1.0412	1.0200
2.8	1.0285	1.0413	1.0200
3.2	1.0286	1.0413	1.0201
3.6	1.0286	1.0414	1.0201
4.0	1.0285	1.0414	1.0200
4.4	1.0284	1.0413	1.0197
4.8	1.0280	1.0410	1.0192
5.0	1.0276	1.0407	1.0187

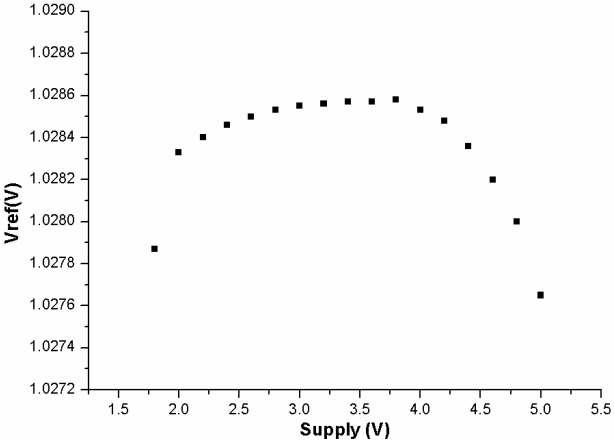

Fig 6: Output voltage vs. supply voltage. Output value varies less than 1mV between 1.8V and 5V.

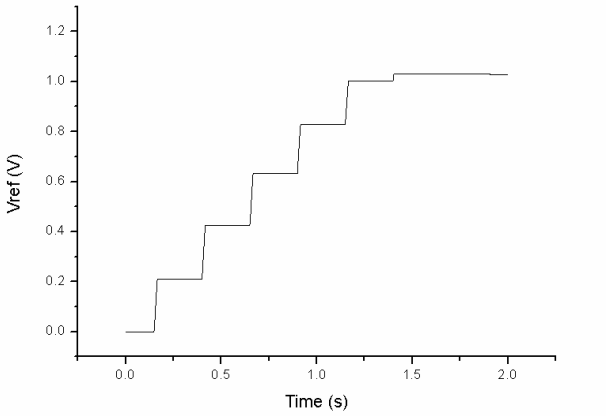

Fig 7: Simulated Start-up of the complete circuit. The external 1µF capacitor is charged periodically until the 1.03V is achieved.

IV. VOLTAGE REFERENCE MEASUREMENT

The circuit was fabricated in XT06 from XFAB a SOI 0.6µm technology [9] and 19 samples were obtained. Figure 8 shows an histogram of all measured values. The mean value of all measurements was VREF=1.029V with a standard deviation of 13mV.

In figure 9 the output value of the voltage reference circuit as a function of supply voltage is shown. The circuit starts

working at 1.65V and the output value varies less than 1mV/V for higher voltages.

Figure 10 shows the measured transient response of the circuit, with a stabilization time of 2 seconds. A comparison between figure 8 and 11 shows a good agreement between simulations and measurements. Both the simulated and measured output voltage versus temperature are plotted in figure 11. The output value varies 0.5mV/ºC, which is within medical devices specifications.

Finally, table 3 shows the measured stabilization time for different supply voltages with the 1µF output capacitor.

TABLE 3: MEASURED STABILIZATION TIME FOR DIFFERENT SUPPLY VALUES

Supply Voltage (V)	Stabilization time (ms)
5	540
3.7	780
2.7	1131
2.2	1820
1.8	3880

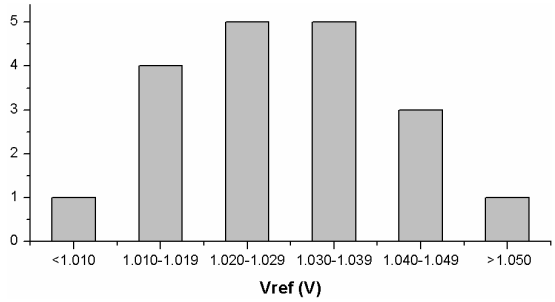

Fig 8: Histogram of measured value in the 19 samples.

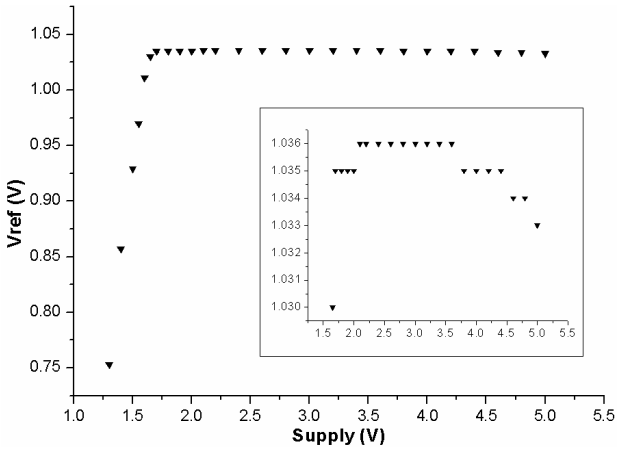

Fig 9: Measured reference value vs. supply voltage. The circuit works from 1.7V. The inset plot shows a detail for the expected supply voltages.

V. CONCLUSIONS

In this work a voltage reference generator was designed, fabricated and measured. The circuit generates a voltage of 1.03V +/- 2% without trimming, while consuming only 200nA. The circuit complies with all specifications and is suitable for integrated circuits in implantable medical devices. To improve in these results, further work is being conducted to reduce silicon area and to achieve a similar consumption without periodically turning the circuit on and off.

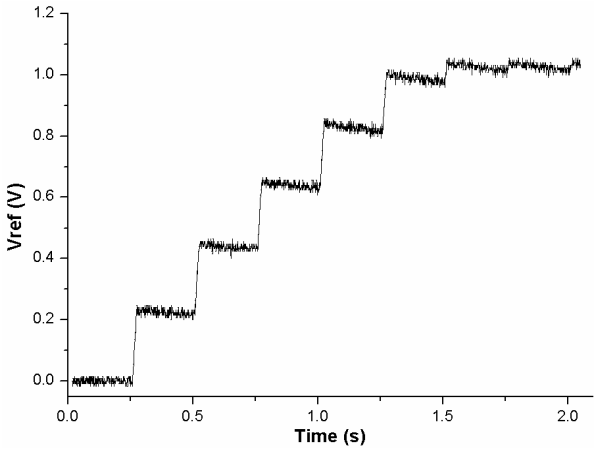

Fig 10: Measured transient response. After several steps, the output begins to stabilize.

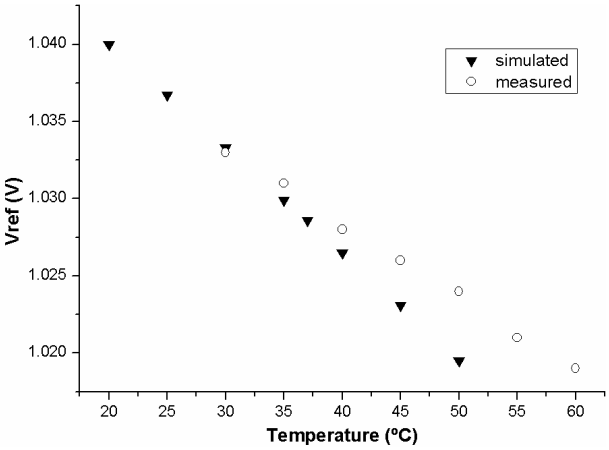

Fig 11: Measured and simulated voltage reference output vs. temperature. Output value varies .5mV/ºC.

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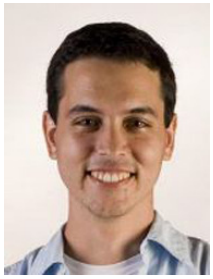

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