Performance of the Bandgap Reference Circuit, designed in a commercial 0.13um CMOS Technology.

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Abstract.

A new all-MOS bandgap voltage reference circuit has been developed and implemented in a standard 0.13-µm CMOS technology. The proposed circuit features dynamic-threshold MOS transistors (DTMOST's).

In order to construct a model of the DTMOST device suitable to run simulations, pre-design characterizations have been carried out.

Measured V_{ref} is 425±15mV (chip-to-chip statistical spread) for 8 samples. The circuit runs at supply voltages down to 0.85V and occupies 0.015mm^2 on the wafer.

The circuit will operate in the radiation environment of high energy physics experiments. An X-ray irradiation facility has been used to examine radiation hardness of the circuit. When being irradiated up to 47 Mrad the reference voltage of the circuit shifts typically only in the range ± 12mV (around 5%).

I. Introduction.

Analog blocks are mandatory parts of today's CMOS ASICs used in high energy physics experiments. Blocks like supply voltage regulators, high quality ADCs and DACs all include a voltage or current reference circuit. The common way to implement reference circuit with a low temperature sensitivity and high power supply ripple rejection is the bandgap reference circuit [1], [2].

With steadily decreasing power supply voltages (Vdd) in present and future deep sub-micron CMOS technologies a design of any bandgap voltage/current reference on-chip becomes a non-trivial task [3]-[5].

The classical voltage summing bandgap reference circuit (BGR) featuring parasitic diodes (p-diffusion in N-well) [6] is not suited for a 0.13µm CMOS technology with a maximum Vdd of 1.2V. It is so because the value of bandgap voltage (V_{gap}) in silicon (1.12V) turns out to be very close to the nominal supply voltage of the process. This causes the circuit to fail.

In this paper we replaced the conventional diodes in the conventional bandgap reference circuit with dynamic-threshold MOS transistors (DTMOST). This allows construct a low-voltage reference circuit able to fit into the reduced supply voltage range of the 0.13µm CMOS technology (see Fig.1).

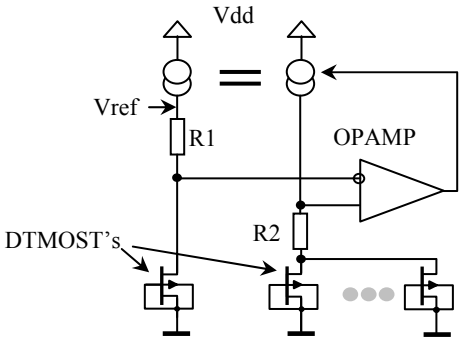

Figure 1: Architecture of the bandgap voltage reference circuit, featuring DTMOST's.

II. Characterisation of the Dynamic-Threshold MOS Transistor (DTMOST).

In 1999 Anne-Johan Annema proposed to use DTMOST structure in CMOS technologies [7]. It is in fact a p-channel MOS (PMOST) transistor with gate, drain and substrate contacts connected together (see Fig.2). In a limited region this device behaves similar to a conventional diode with exception: it needs far lower bias voltage to operate (see Fig.3).

The exponential behaviour of the voltage-to-current characteristic is of primary importance because it enables us to construct a current source, which delivers a current that is proportional to the absolute temperature (PTAT). This can be used to implement a mechanism of temperature compensation in a bandgap reference circuit [8]. The conventional diode has an exponential voltage-to-current relationship above 650mV while the DTMOST device is exponential within a region from 100mV to 220mV (see Fig.3).

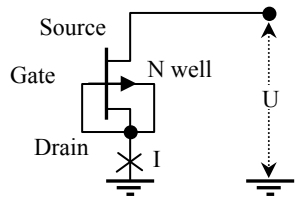

Figure 2: DTMOST device on the basis of PMOST.

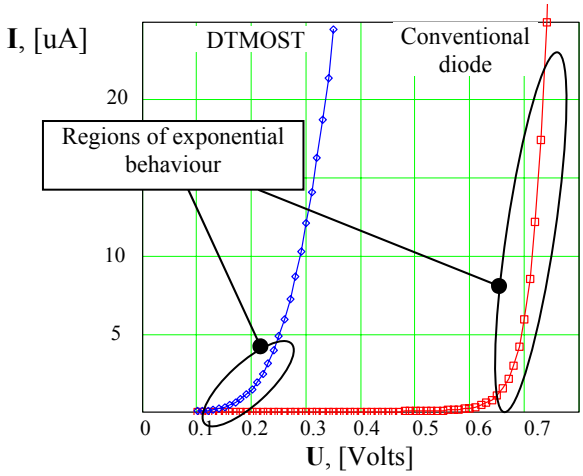

Figure 3: Current-to-voltage characteristics for both DTMOST configuration and conventional diode configuration.

In order to design a complete bandgap reference circuit the DTMOST structures have been characterized and modelled. The current-to-voltage characteristic Id(Vgs) of the DTMOST has been measured at various temperatures in a temperature chamber. As expected, voltage across the DTMOST is conversely proportional to the absolute temperature (see Fig.4).

The temperature gradient is approximately -0.8mV/ºC. By the approximation of the lines to the low temperature region the effective bandgap voltage is estimated to be 420mV (see Fig.4).

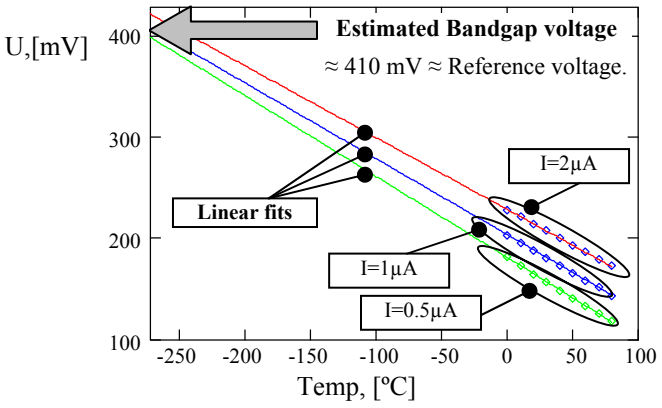

Figure 4: Voltage across the DTMOST at various currents as a function of temperature.

III. Voltage reference circuit.

The complete voltage bandgap reference circuit consists of the DTMOST devices, a pair of cascoded current sources and a two-stage operational amplifier (see Fig.5). According to the measurements voltage across the DTMOST is Conversely Proportional to Absolute Temperature (CTAT). On the other hand, the voltage across the chain of resistors is Proportional to Absolute Temperature (PTAT) since the current through the DTMOST's goes up as temperature rises

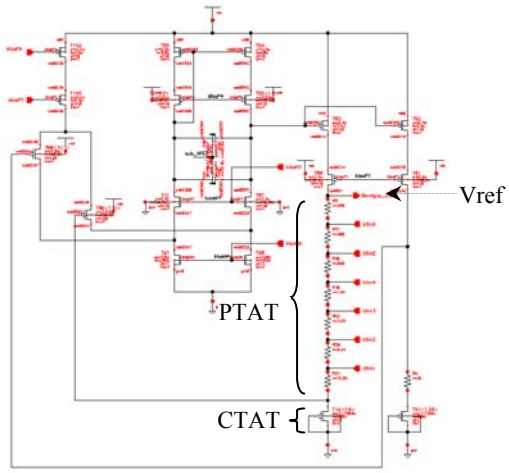

Figure.5: Schematic of the voltage reference circuit featuring DTMOST's.

After an appropriate adjustment, superposition of the PTAT and the CTAT voltages results in a temperature insensitive reference voltage (see Fig.6).

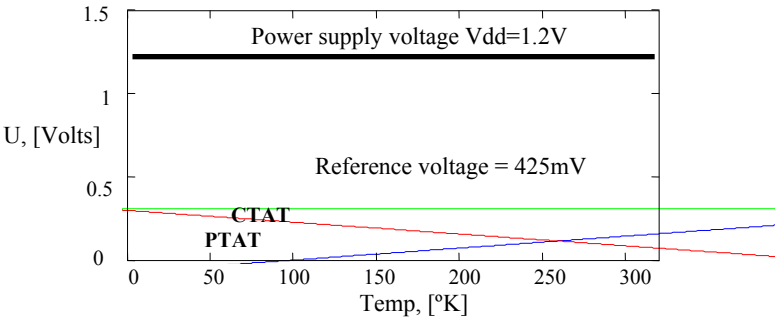

Figure 6: Temperature behaviour of the voltages in the circuit.

All the biases needed for operation of the circuit are generated on-chip.

IV. Experimental results.

A. Temperature dependence of the reference voltage.

Eight chips to test were at our disposal. In order to vary the value of the PTAT resistor (see Fig.5) we broke it in sections, which can be externally bypassed. In this way the slope of the PTAT voltage has been trimmed to the slope of the CTAT voltage so as to get the minimal temperature coefficient of the reference voltage. Under such condition, the reference voltage to temperature relation is a parabola with maximum deviation less than 1mV within the range from 0ºC up to 80ºC (see Fig.7). When untrimmed the temperature coefficient of the reference voltage takes a turn to the worse and comes to the value of 0.05mV/ºC.

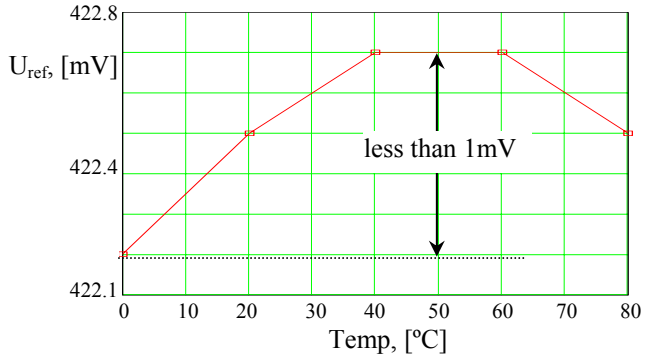

Figure 7: The measured reference voltage as a function of temperature.

B. *Sensitivity of the reference voltage to the power supply variation.*

The designed bandgap circuit needs at least 0.85V supply voltage to operate. It is operational amplifier that limits the value. Effective bandgap voltage in the DTMOST (420mV) and saturation voltage of the current source transistors (100mV) set, in fact, minimum supply voltage of the circuit at the level of 520mV.

$$Vdd_{min} = Veff_{bandgap\ DTMOST} + Vds_{sat} = \\ = 420mV + 100mV \approx 520mV$$

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These measurements demonstrate that above 0.85V the reference voltage is slightly sensitive to variations of the supply voltage (see Fig. 8). The slope of the line is 3.3mV/V.

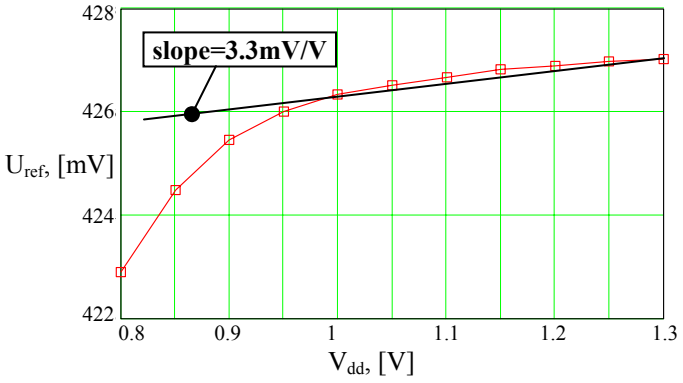

Figure 8: The measured reference voltage as a function of power supply voltage.

C. *Fluctuation of the reference voltage caused by X-ray irradiation.*

We used the CERN's in-house X-ray facility [9] for the irradiation of the chips. The effect caused by irradiation consists in the shift of the reference voltage while the circuit remains fully operational. As depicted in Fig.9 the reference voltage shifts by a few millivolts after it has been irradiated with X-rays dose as high as 67Mrad.

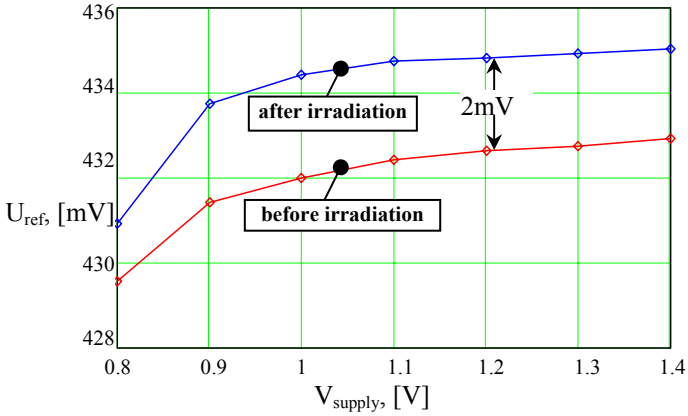

Figure 9: The measured reference voltage as a function of power supply voltage before and after irradiation. Accumulated dose is 67 Mrad.

The change of the reference voltage has been monitored in the time of the irradiation. We tested 5 chips and have seen that the reference voltage does not demonstrate an identical behaviour. The conclusion is that the reference voltage deviates in the range of ± 12mV (see Fig.10).

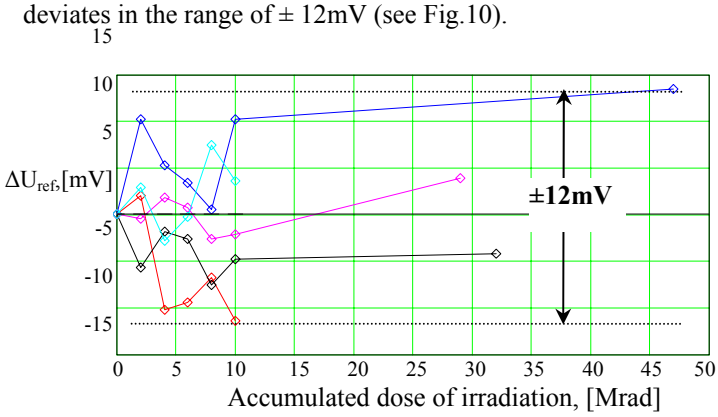

Figure 10: The measured shift of the reference voltage in the time of irradiation.

We have compared the reference voltage to temperature characteristics (see Fig.11) before and after the irradiation in order to find out the most vulnerable part in the design. The parabola shape indicates that the circuit operates in the vicinity of the optimum point in both cases. The optimum operation point is set by the mechanism of temperature compensation wherein only the DTMOST's and resistors (see Fig.1) have been involved.

It means that the irradiation does mainly on the components of the operational amplifier causing offsets and results in temperature independent shift of the reference voltage.

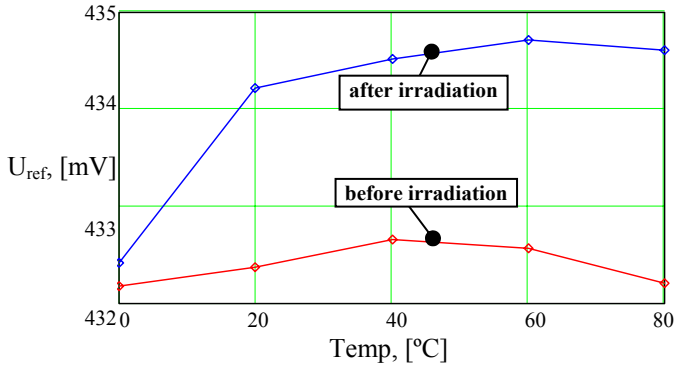

Figure 11: The measured reference voltage as a function of temperature before and after irradiation. Accumulated dose is 67 Mrad.

D. Chip-to-chip spread of the reference voltage.

In some applications not only stability of the reference voltage is important but its absolute value as well. The absolute value differs from chip to chip and it is caused by fabrication process variation. With few samples available we can roughly estimates chip-to-chip spread of the value of the reference voltage. It turned out to be confined in the range of 30mV (see Fig.12).

Mismatch of components in the layout is at the bottom of the chip-to-chip spread. According to Monte-Carlo simulations in CADENCE, mismatch of the input transistors of the OPAMP (see Fig.1) is the major course of the spread of the reference voltage (σ_{opamp}=5mV). Mismatch of the resistors R1,R2 (σ_{res}=0.5mV) together with mismatch of the DTMOST devices (σ_{DTMOST}=2.85mV) contribute far less. Altogether it yields for overall chip-to-chip spread of the reference voltage as follows:

$$\sigma_{\Sigma} = \sqrt{(\sigma^2_{opamp}+\sigma^2_{res}+\sigma^2_{DTMOST})} = 5.7\text{mV}$$

The range of variation of the reference voltage is:

$$\Delta V^{simulations}_{ref} = 5\cdot\sigma_{\Sigma} \approx 30\text{mV}.$$

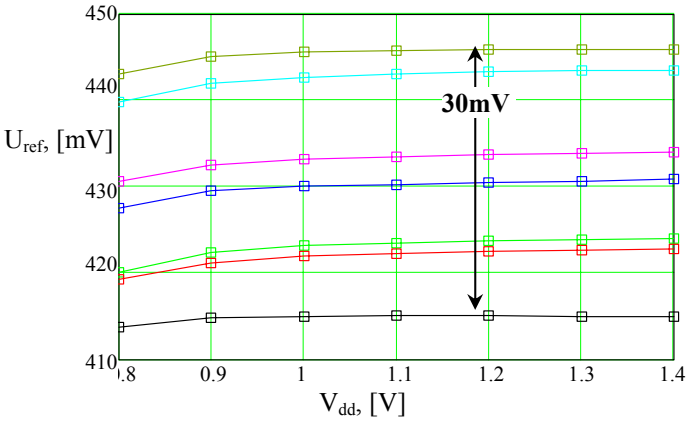

Figure 12: The measured chip-to-chip variation of the value of the reference voltage.

IV. Conclusions.

A new bandgap voltage reference circuit has been designed in standard 0.13um CMOS technology. This design features DTMOST devices in order to squeeze into a low power-supply range of the technology.

The main specifications of the design are:

power supply voltage: 0.85V < Vdd <1.4V,

output reference voltage: Vref = 425±15mV (chip-to-chip statistical spread),

temperature dependence of the reference voltage in the range from 0ºC up to 80ºC: <1mV (when trimmed)
0.05mV/ºC (when untrimmed),

sensitivity of the reference voltage to the power supple voltage variation: 3.3mV/V,

fluctuations of the reference voltage caused by X-ray irradiation in the range up to 47Mrad: ±12mV.

V. Acknowledgements.

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VI. References.

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