

# A Temperature and Voltage Measurement Cell for VLSI Circuits

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## Abstract

*A Temperature and Voltage Measurement Cell (TVM Cell) for VLSI circuits has been developed. It requires less than 1 mm<sup>2</sup> of core area (for a 2 μm CMOS technology) and only 4 I/O pins. It can be integrated into any CMOS VLSI circuit. It permits the measurement of the Circuit Die Temperature (T) and its Core Power Supply Voltage (V) while the chip is operated normally in a system.*

*It achieved simultaneously an accuracy better than 50 mV and 3° C. Output values are averages of the parameters during a 1 ms period.*

## 1 Introduction

In large and complex computer systems, thermal dissipation and power distribution problems are very critical. And they will become so more and more in the future as it is expected that advances in integration and performance will go with an increasing density of electrical power. A correct analysis of those problem is essential for systems reliability.

Theoretical studies and simulations can be performed but, although they are very useful, they cannot be very accurate since they cannot handle all the parameters and the models are quite simple. For example, it is not easy to know the power consumption of a part, which may depend on its activity, or the efficiency of a cooling air-flow which may depend on the local relief of a pc board.

Direct experimentation can be performed on existing systems by introducing sensors. However, this is a quite complex operation that can be executed only on prototypes and not automatically. Moreover, it will provide information at the board level but not at the chip substrate level.

As we were designing an array processor for real-time image processing, it appeared that the possibility of measuring the junction temperature  $T$  and the core

power supply voltage  $V$  of each processor could help to obtain the maximum of performance from the system by allowing it to operate securely closer to its limits.

This is why we designed a cell dedicated to be inserted into each processor using very little silicon area and able to measure the  $T$  and  $V$  parameters with an accuracy sufficient for our needs. This temperature and voltage measurement cell (TVM cell) can be inserted into any CMOS VLSI circuit. It uses less than 1 mm<sup>2</sup> of core area (for a 2 μm CMOS technology) and only 4 I/O pins.

Our method is based on an indirect measure of two technological parameters that both depends on  $T$  and  $V$  but not in the same way. The choosen parameters are the transistor and diffusion resistances.

## 2 Prototype TVM cell

Figure 1 shows the organisation of the prototype TVM cell. It is constituted of 2 major parts:

- A parametrable ring oscillator whose operating frequencies can be, from its design, be settled as mainly depending on n-diffusion, p-diffusion, p-transistor and n-transistor resistances.
- An 18-bit counter, with an integrated scanpath, used for the measurement of the oscillator frequency.

Four I/O pins are needed: a scanpath input, a scanpath output, a scanpath clock and a validation for the operation of the oscillator.

The prototype cell was a research project and its purpose was also to test the principle of a bidirectional scanpath. So a fifth input has been added for that purpose, it specifies the direction of transfert.

An heating resistor has also been included in the prototype as a convenient way of changing the substrate temperature.

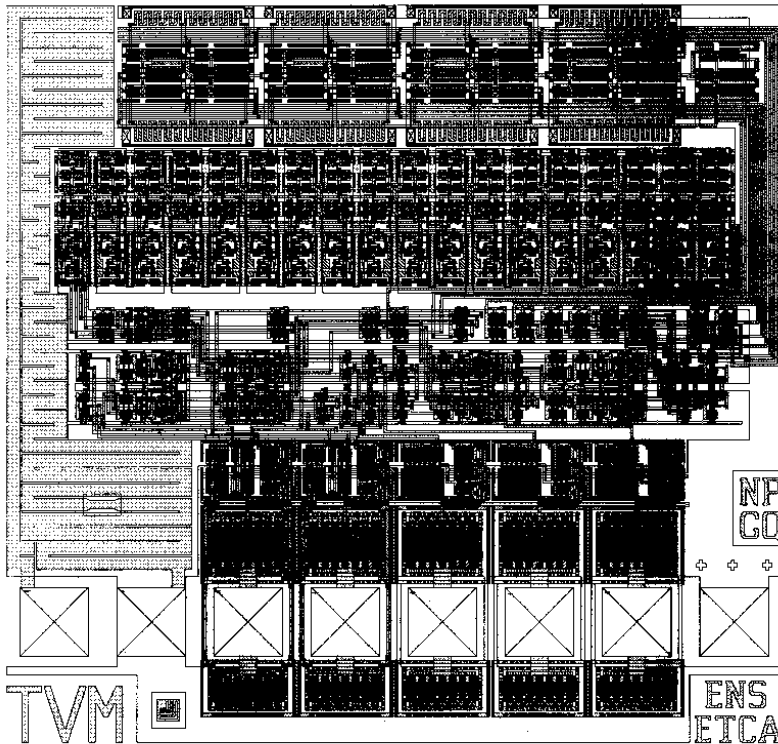


Figure 2: Prototype TVM cell layout and floorplan

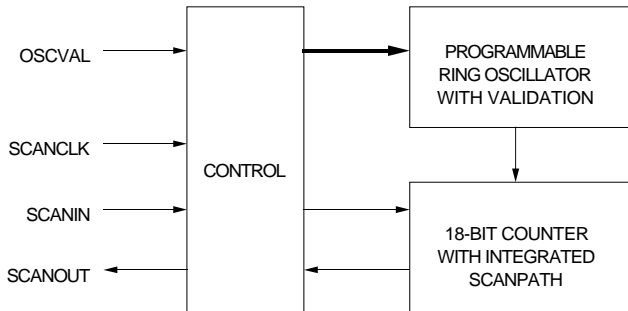


Figure 1: Prototype TVM cell organisation

Figure 2 shows the layout and floorplan of the Prototype TVM cell.

Figure 3 shows the elementary inverting delay cell.

Input and output of the cell are buffered. This is necessary to keep sharp edges across the oscillator. The input and output buffer are quite powerful so that they account for a very little part in the total cell delay.

During operation exactly one of the four CMOS switches is activated and the corresponding path is selected for the delay. This delay depends mostly of one selected parameter. For diffusion resistance, the de-

lay appear on both high-to-low and low-to-high transitions. For transistor resistance, it appear only one transition but it is twice as long.

The resistance values indicated for the transistors are the one of their on-state considering a slow process. The capacitance on the nodes are approximately of 0.5 pF for the output of the first inverter, 4.0 pF for the load of the test delay resistance and 0.3 pF for the output of the last inverter. The delay is approximately the same on every path and it depends approximately by 75 % of the targeted parameter. The other 25 % of the delay depends of an average of the n and p transistor parameters in an identical way for the four pathes.

The TVM cell operates in three steps:

First, the counter is cleared using the scanpath. Simultaneously, the chosen path in the ring oscillator is selected also using the scanpath.

Second, the ring oscillator is activated as a clock for the counter during a fixed period (typically 1 ms).

Third, the counter is read using the scanpath.

The TVM cell permits the external measurement of the four oscillator frequencies:  $F_{dn}$ ,  $F_{dp}$ ,  $F_{tn}$  and  $F_{tp}$ . Those frequencies are dependant on the power supply voltage, the circuit die temperature and technological



	Voltage	Temperature
avg. error	0.006 V (0.3 %)	0.49 °C (0.8 %)
max. error	0.042 V (2.1 %)	1.85 °C (3.1 %)

Table 2: TVM accuracy test results

The most natural ones are polynomial functions and the simplest way of obtaining them is to use the least square method over the calibration set. When doing this, it is necessary that the number of coefficients of the polynomial is less than the number of elements of the calibration set.

Tests have been carried out using polynoms of 4, 3 or 2 variables and with degrees ranging from 1 to 5. As it could have been expected, the best results have been obtained using only the  $F_{dn}$  and  $F_{tn}$  couple of parameters. The use of the other ones is redundant and induces higher noise. It has also been found that the optimal degree for the polynomial is 4 with a 25-value calibration set.

The fourth degree polynomial of  $F_{dn}$  and  $F_{tn}$  obtained by the least square method over the 25-value calibration set has been used for the accuracy test. Table 2 shows the average and maximum error of the TVM cell. The error percentage is relative to the range of operation: 2 V (between 4 and 6) for the voltage and 60 °C (between 20 and 80) for the temperature. The test set is an 81-value one covering the whole operating range with a voltage step of 0.25 V and a temperature step of 7.5 °C.

The obtained accuracy is better than 50 mV and 3°C (a margin has been added for the temperature one since a relative scale was used for it).

The measured values are the averages of the targeted ones during a 1 ms period. This is long relatively to the temperature variations but very short relatively to the possible voltage ones. It must be noticed that the TVM cell is able to perform only 1 ms averages measures of the  $V$  parameter.

#### 4 Industrial TVM cell

Since the prototype cell has shown that the couple ( $F_{dn}, F_{tn}$ ) is sufficient alone for the TVM cell, the industrial version does not need to provide the measure of the other parameters.

In order to increase its accuracy, it has been chosen to include two distinct oscillators: one whose operating frequency depends mainly on n-diffusion resistance and the other whose operating frequency depends mainly on n-transistor resistance. Two distinct counters have also been implemented. Figure 5 shows the organisa-

tion of the industrial TVM cell.

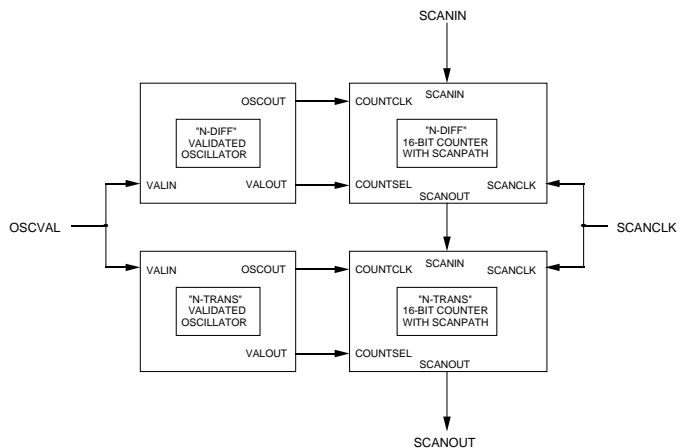


Figure 5: Industrial TVM cell organisation

Doing so, the percentage of the targeted parameter in the measure is increased since the multiplexer switches are no longer in the path. Simultaneous measure of the two frequencies is expected to provide less noise than the sequential one.

#### 5 TVM System

TVM cells are very easy to use. The main problem is the need for an host system with a physical bus and a processor. However this can be found into any computer system. Figure 6 shows the organisation of a TVM system.

Using read and write operations, the host processor can easily write and read all the counters through the concatenated scanpaths. It can also activate the oscillator for a given time. The physical interface between the system bus and the cells is very simple and can be easily integrated into a monochip programmable gate-array.

A background, low-priority process can periodically measure the  $T$  and  $V$  parameter of every chip containing a TVM cell (This is a very low CPU load). It can keep track of the parameter for problem analysis applications or it can only check their range and send warning when an abnormal situation is detected.

Calibration must be made individually for every circuit and the coefficients of the polynomial providing ( $T, V$ ) from ( $F_{dn}, F_{tn}$ ) are specific for every circuit. They may be obtained when the chips are tested during their fabrication or by a global calibration of the whole system when it is possible.

Due to its scanpath basis, the TVM system operates very nicely in conjunction with Boundary Scan or

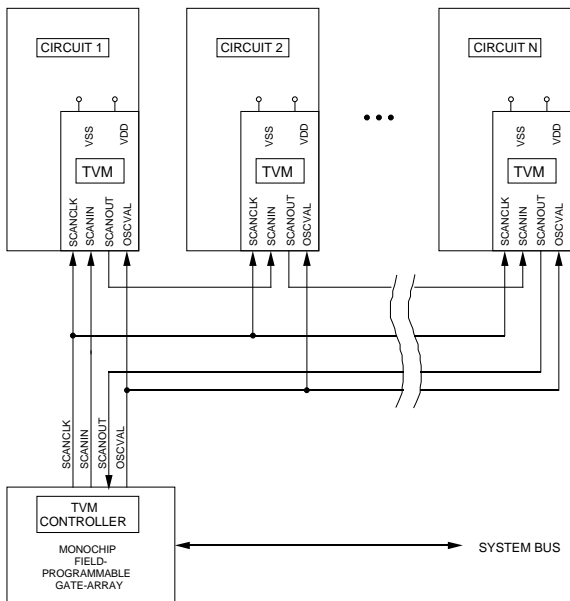


Figure 6: TVM system organisation

LSSD test techniques. In that case, it can share 3 of the 4 dedicated I/O pins necessary for their implementation and needs only 2 more input pins. Since test scanpaths are usually not used while the chip operates normally in a system, they may be used to perform the  $T$  and  $V$  measures even in this case.

## 6 The ETCA application of TVM cells

At ETCA, we develop an array processor for real-time image processing. This machine will house 1024 elementary data-flow processors in 512 biprocessor chips [1]. Thermal dissipation and power distribution problems have been solved conveniently using empirical methods. However our main problem is to keep the junction temperature of each processor as low as possible for two main reasons.

The first one is the system long term reliability. Since the machine houses hundreds of processor chips, it is essential that every one has a very high reliability. The lower is the operating temperature the higher is the chip reliability.

The second one is the need to raise the system frequency as high as possible (it corresponds to the maximum pixel acquisition frequency for real-time image processing). The lower is the operating temperature the higher is the frequency at which the system still operates correctly.

A TVM cell has been integrated into every biprocessor chip in the machine. The two counters have been inserted in the processors datapathes. No additional

input/output pads have been necessary for it since it uses the same ones that the scanpath used for the test and the programming of the processors. The total area of this cell is less than  $0.5 \text{ mm}^2$ .

Until now, tests on our industrial TVM cells have not been completed. It has been observed that the  $F_{dn}$  and  $F_{tn}$  does increase with the  $V$  parameter. It has also been checked that their average statistical variation when  $T$  and  $V$  are constant does not increase significantly when the chip goes from the inactive state to the running state (both are below 0.1 %).

## 7 Conclusion

A prototype Temperature and Voltage Measurement (TVM) cell has been developed and tested. Its goal is to perform on-site and real-time measure of the die temperature and the core power supply of CMOS VLSI chips. It can be used even while the chips are normally operated in their system. It permits an efficient on-site analysis of thermal dissipation and power distribution problems and is expected to increase systems reliability and performance.

The prototype TVM cell includes 1418 transistors in a  $1.43 \text{ mm}^2$  area including I/O pads. It includes an 18-bit counter and a parametrable ring oscillator whose operating frequency can be programmed as depending on n-diffusion, p-diffusion, n-transistor or p-transistor resistances. Frequencies measurements are made sequentially and the  $T$  and  $V$  parameters are computed from them.

Best results have been obtained using the (n-diffusion, n-transistor) couple.  $T$  and  $V$  are computed via a fourth degree polynomial of  $F_{dn}$  and  $F_{tn}$ . This polynomial has been calculated by the least square method over a 25-values calibration set within  $4\text{V} - 6\text{V}$  and  $20^\circ\text{C} - 80^\circ\text{C}$  ranges. An accuracy better than  $50 \text{ mV}$  and  $3^\circ\text{C}$  have been obtained.

A TVM cell has been integrated into a data-flow processor developed at ETCA for image processing. This processor is intended to be used into large arrays, ranging from 64 to 1024 processors. In such systems, power distribution and thermal dissipation are very critical and TVM cells are expected contributing as a key factor to their reliability and performance.

## References

- [1] G.M. Quénot, B. Zavidovique, "A Data-Flow Processor for Real-Time Low-Level Image Processing," *EURO-ASIC 91*, may 1991, Paris.