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Delay estimation and measurement circuit for a high-speed CMOS clocked comparator

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Abstract—Comparators are a critical element of Analog-to-Digital converters (ADCs) intended to operate in a harsh environments such as the automotive. The influence of temperature on key comparator properties such as the delay must be well understood to maximize their speed. In this paper a Double-Tail latch analysis leads to an analytical expression for the delay to more accurately guide the design over a wide temperature range. The results given by this model agree well with spice post-layout simulation for a CMOS 0.18- μm SOI process, taking into consideration both process and temperature variations. To verify experimentally the correctness of the model we also propose a novel on-chip fully digital asynchronous architecture to measure the delay of the comparator, robust against extreme temperature variations.

Index Terms—latch, double tail, comparator, delay, measurement circuit, Monte-Carlo Analysis, PVT, temperature

I. INTRODUCTION

Comparators are a critical element of Analog-to-Digital converters (ADCs) intended to operate in a harsh environments such as the automotive. Reliable and robust operation must be ensured under stringent manufacturing (cost, yield, etc.) and operating conditions (voltage fluctuations, mechanical stress, etc.) over the lifetime of the part. Among these constraints, the operating temperature range (-50°C to $+175^\circ\text{C}$) is arguably the most difficult one. Hence, the influence of temperature on key comparator architectures balancing speed, power, resolution must be well understood. In CMOS technology, the best compromise is usually obtained by the use of clocked comparators, which rely on cross-coupled positive feedback circuits that latch to the supply rails. They must be initialized (reset) to a given metastable starting state, from which they will depart and follow a trajectory to one of two stable states depending on the input signal polarity. In most clocked comparators, the total decision time of the comparator can be understood as the concatenation of typically one or more linear phases, followed by one exponential phase.

To design a comparator for a given ADC it is essential to know the time needed to reach a decision when a small input voltage difference is applied. In this paper we formulate an improved analytical model to estimate the double-tail comparator delay over an extended temperature range (-50°C to $+175^\circ\text{C}$).

The experimental measurement of the delay over such a wide temperature also poses an interesting challenge. Earlier works have used simple as well as complex circuits for delay extraction. For example, in [1] one generates a DC voltage that is proportional to the average delay, thus avoiding the routing of high speed signals of chip. This simple solution is strongly influenced by the parasitic capacitance and its variation. More sophisticated approaches such as Time-to-Digital converters (TDCs) [2], achieve fine time delay resolution, but are hard to design against extremely large process-voltage-temperature (PVT) variations. In this paper we introduce a novel wholly digital asynchronous architecture for measurement of comparator delay that strikes a good balance between accuracy and area, and is robust with respect to extreme measurement conditions.

This paper is organized as follows; first we describe the behaviour of the double-tail (DT) comparator in Figure 1. This review is followed by the development of a new analytical model for estimation of the DT propagation delay valid for small differential input voltages, where the delay sets the limit for the achievable conversion rate. We also give the biasing conditions for extraction of the small signal parameters of our model. Afterwards, in Section III we discuss a novel on-chip digital circuit able to measure the comparator time delay accurately across PVT variations. The results of our model over process and temperature variations are discussed in Section IV. The model fit to a $\pm 6\sigma$ Gaussian Monte-Carlo simulation and is compared to a previous model [3]. This last section also presents the preliminary results of the proposed measurement circuit.

II. COMPARATOR DELAY MODEL

The DT comparator [4], shown in Figure 1, has become popular in the past few years, together with its variations [3], [5]. The key idea is to cascade a preamplification stage and a regenerating latch to decouple the design constraints of the two amplifiers. This configuration also improves the voltage headroom. Here we develop an original model for the propagation delay taking into account the current drawn by transistors M6-M7, to improve the accuracy with respect to previous works [3].

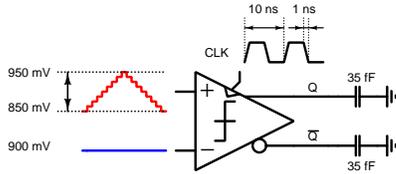


Fig. 4: simulation setup for the spice and the matlab model

75% of the voltage swing. The values kept are for each run the worst delay calculated.

Figure 5 compares the estimation of the time delay to the simulated circuits in SPECTRE from from -50°C to $+175^{\circ}\text{C}$ and the standard deviation. The error on the estimation varies from -67ps to $+94\text{ps}$ for the proposed model. This represents a maximum error of 4.2 % due to a non accurate estimation of transconductance over the time and over the temperature.

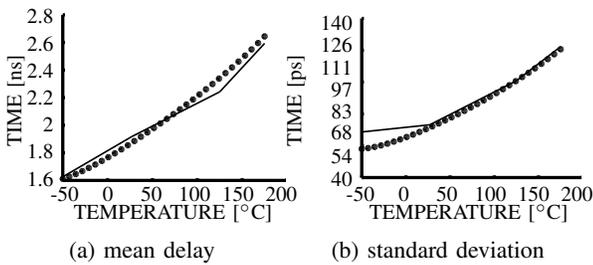


Fig. 5: spice (-) and proposed analytical model (.) comparison of the mean time delay over temperature at $6\text{-}\sigma$ Monte-Carlo analysis

Figure 6 compares the estimation of the time delay to the simulated circuits in SPECTRE from from -50°C to $+175^{\circ}\text{C}$ and the standard deviation according the equation from [3]. The previous model of the double tail depicts an error on the estimation from -71ps to $+264\text{ps}$ which represent an increased error of 80 % over the full temperature range compared to our model with and a reduced error from 27°C to 150°C .

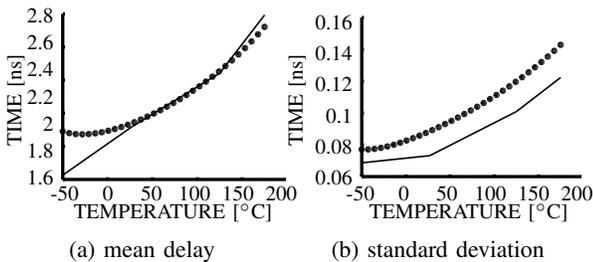


Fig. 6: spice (-) and analytical model from [3] (.) comparison of the mean time delay over temperature at $6\text{-}\sigma$ Monte-Carlo analysis

On the standard deviation the model from [3] exhibit an error from $+8.4\text{ps}$ to 20.5ps while the proposed model commit an maximum error of -8.96ps .

B. measurement circuit results

To verify the correct extraction of the comparator delay, and the time to reset, The proposed measurement circuit have

been simulated post layout with a frequency divider of 64. The maximum frequency after the divider does not exceed 5.3 MHz.

With a verilog-a reference comparator with a time delay of 1.5 ns followed by inverters, the performances resulting from the circuit proposed are presented in the table III. Those results are compared to the simulation setup of reference presented Figure 4.

TABLE III: delay extraction from the proposed circuit for a comparator of reference

temperature	corner	T_{delay} from circuit	T_{delay} from Fig. 4	error
-50°C	SS	1.627 ns	1.651 ns	24 ps
-50°C	FF	1.636 ns	1.655 ns	19 ps
175°C	SS	1.634 ns	1.66 ns	26 ps
175°C	FF	1.645 ns	1.667 ns	22 ps

At the output of the comparator of reference extra inverters added are used to provide a capacitive load to the latch equal between the test setup. The error between the two simulation setup is less than 30 ps with a systematic error which can be explained by a different load on the inverters. The variation across corners is less than 5 ps for a maximum jitter of generated clock divided of 140 Hz, and a frequency measurement on 25 clock period of 2.9 MHz. Due to its asynchronous nature the circuit is hand-laid out in a $43.43\text{ }\mu\text{m} \times 30.3\text{ }\mu\text{m}$, a surface 3.3 times larger than the DT one.

V. CONCLUSION & FUTURE WORK

We have presented a new model for DT delay estimation, more accurate over an extended temperature range w.r.t. previous works, verified using $6\text{-}\sigma$ Monte-Carlo simulation runs under the SPECTRE simulator using a CMOS $0.18\text{-}\mu\text{m}$ SOI process. We also introduced a novel all-digital comparator delay measurement circuit for on-chip measurements based on a self-oscillating circuit with a differential frequency measurement methodology. The simulation results using a verilog-a reference comparator exhibit a low sensitivity on the process and temperature variation. A test chip was designed and sent for fabrication, experimental measurements will soon follow.

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