Testing CMOS circuits at 50ps resolution with single-photon avalanche detectors

S. Cova, C. Porta, F. Stellari and F. Zappa
DEI, Politecnico di Milano
P.zza L. da Vinci,32 – 20133 Milano, Italy
zappa@elet.polimi.it

J.C. Tsang
IBM T.J. Watson Research Center
Yorktown Heights, NY, USA

Abstract

A non-invasive characterization of a fast CMOS ring oscillator is reported. The optoelectronic technique exploits infrared emission from hot-carriers in high-field regions of switching transistors. By means of a fast solid-state single-photon detector (Single Photon Avalanche Detector SPAD), high time resolution and sensitivity are obtained. Experimental data with 50ps resolution enable to measure systematic variations of the period and jitter of switching transitions due to phase noise in a ring oscillator. The luminescence of p-channel MOSFET’s, previously reported to be barely detectable, is also measured.

1. Introduction

Excess delays and skews are nowadays very important factors that limit the performance of high-speed ULSI circuits [1]. As feature sizes keep shrinking, Mechanical Probe Testers become almost useless and Electron Beam Testers are not fully adequate. Alternative methods are sought for probing circuits at single transistor level [2], [3]. An optoelectronic inspection technique based on hot-carrier luminescence has been shown to be a valuable tool for testing complex circuits and single transistors [4], [5].

We report here measurements of the faint luminescence of a fast CMOS ring oscillator of IBM, performed with a fast silicon Single-Photon Avalanche Detector (SPAD), developed at Politecnico di Milano [6]. The goal was to investigate the time resolution and sensitivity attainable in such test.

2. Experimental set-up

A microscope (see Fig. 1) collects photons emitted from the Device Under Test (DUT) and focus them onto the very small detector (10µm active area diameter). The observed area can be varied from a single inverter up to the whole chip by changing microscope objective (see Fig. 2).

The DUT is a ring oscillator running at

Figure 1. Experimental set-up.
73.4 MHz. A chain of 47 inverters is followed by an on-chip counter, that demultiplies the frequency by 32 (see Fig. 3). A squarewave signal is available at the counter output, connected to an external 1 kΩ load resistor. A synchronization signal is obtained with an ECL comparator.

The SPAD detector operates at room temperature in geiger mode with 22 V bias. The detector has low intrinsic noise (dark-counting rate of 300 counts/second) [6]. The Active Quenching Circuit (AQC) [7] ensures short-deadtime operation of the SPAD and produces digital pulse accurately synchronous with the detected single photons. A Time-Correlated Photon Counting apparatus (TCPC) [8] measures the photon arrival time with respect to the synchronization signal. With a high number of events, a measurement histogram that represents the optical waveform is obtained.

3. Single-inverter observation

With a 50x collection objective, the observation is limited to only one inverter of the ring oscillator (see Fig. 2a).

Fig. 4 illustrates the results obtained with a ring supply voltage of 5 V. The measured time range covers one period of the squarewave at the counter output, i.e. 435.9 ns (the output frequency is 73.4/32=2.294 MHz). The inverter emits 32 pulses within this period.

There is a tradeoff between reasonably short acquisition time and sufficiently high number of measured events, as necessary for reducing statistical fluctuations and observe in detail the waveform features. A 20 minutes acquisition time was adopted as a suitable compromise.

3.1. Internal cycle-time

The pulses should be equally spaced by 435.9 ns/32=13.62 ns, since the interval between consecutive pulses corresponds to the oscillator internal cycle (i.e. two round trips in the ring). On the contrary, systematic deviations from constant interval are observed in the data of Fig. 4, similar to those already reported in [9]. As shown in Fig. 5, 16 consecutive cycles shorter than the nominal internal period are followed by 16 longer ones. This behaviour is correlated to the counter output waveform, at high level (T_ON) during 16 cycles of the internal ring and at low level (T_OFF) in the following 16 cycles. The 16 shorter intervals in Fig. 5 (square symbols) add up to T_ON=215.1 ns; the longer ones (dot symbols) add up to T_OFF=221.1 ns. These
values are in excellent agreement with the values directly measured on the squarewave output. The deviation of the duty cycle from 50% is probably caused by a change of the supply voltage of the oscillator, due to the current in the load resistor.

3.2. Internal jitter

The measured width (Full Width Half Maximum FWHM) of the pulses in Fig. 4 increases with the pulse position within one external period, as shown in Fig. 6. Since the waveforms are measured by averaging over many repetitions, a jitter in the time position of the emitted pulse with respect to the synchronization signal contributes to the width of the averaged waveform. The progressive widening thus denotes a cumulative effect of the various cycles on the time jitter of switching transitions. Thanks to the optoelectronic technique, useful insight in the circuit operation can be gained by observing this effect, related to the oscillator phase noise.

The long (500ns) instrumental time scale, used for observing all pulses within one period, limits the time resolution to about 100ps. The effect on the jitter is better observed in measurements on a subset of pulses performed with a shorter (200ns) time scale, where the intrinsic time resolution of the detector is better exploited. As shown in Fig. 7 an average increase of 1.24ps per cycle is confirmed.

3.3. Time resolution

The time resolution attained was checked in measurements performed with the shortest time scale (25 ns) of the TCPC apparatus. The measured pulse waveform of a single inverter has 50ps-FWHM (see Fig. 8). It results from the convolution of the true waveform of the inverter pulse with the intrinsic response of the detector. The latter is independently measured with ultrafast laser pulses and has about 38ps-FWHM.

![Figure 5. Cycle-time variation.](image1)

![Figure 6. Pulse-width variation.](image2)

![Figure 7. Short time-scale data.](image3)
4. Observation of many inverters

In measurements performed by collecting the light from a wider area (see Fig. 2b), the transitions of various inverters are observed. The test system has the capability of discerning the light pulses from neighbouring MOSFET’s, as illustrated in Fig. 9. A longer acquisition time (one hour) was here employed to obtain a higher signal-to-noise ratio, that enhances the capability of observing small features. Pulses from different transistors are separately observed, at time positions that are multiples of the basic step, given by the propagation delay of a single inverter \( T_p = 143 \text{ps} \). It may be noted that also the p-MOSFET pulses are clearly visible in Fig. 9 (denoted by a letter p), whereas in previously published works they had been reported to be barely detected [5], [9].

5. Conclusions

This work demonstrates that fast SPAD’s provide 50ps FWHM resolution in the detection of MOSFET’s luminescence (Fig. 8). Signal characterization with 20GHz equivalent analogue bandwidth is thus enabled with the optoelectronic technique, that appears to be a valuable tool for circuit testing and debugging. We have employed the experimental set-up for quantitatively evaluating the electrical performances of a ring oscillator, identifying systematic (Fig. 5) and statistical (Fig. 6) variations of the internal ring cycle. Furthermore, thanks to the high quantum efficiency of the detector, we have been able to clearly detect and measure the faint luminescence pulses coming from both n-channel and p-channel MOSFET’s.

6. References