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High-Speed CMOS Circuit Testing by 50 ps Time-Resolved Luminescence Measurements

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Abstract—Noninvasive characterization of CMOS ring oscillator with 50 ps resolution is obtained by exploiting the broad-band infrared emission from switching transistors. A fast silicon single-photon avalanche-diode (SPAD) is used to attain high sensitivity and time resolution. Switching transitions of both n- and p-channel MOSFETs are measured and the main features in the circuit operation are characterized. Systematic variations and increased jitter of switching transitions due to phase noise are accurately measured.

Index Terms—Circuit testing, jitter, luminescence, picosecond imaging for circuit analysis (PICA), ring oscillator, single-photon avalanche-diode (SPAD), time correlated photon counting, ULSI.

I. INTRODUCTION

The steady progress in the development of a faster and denser circuit makes the task of testing electrical signals within ULSI circuits increasingly complex. The currently available techniques, i.e., mechanical testing, electron beam testing (EBT), and photon emission microscopy (EMMI) [1], are expected to become progressively challenging [2]. Optical probing, based on a laser beam excitation of the circuit under test [3], [4], is available as an analysis technique also for backside investigation [5].

A different optical inspection technique, based on photoluminescence, known as the picosecond imaging for circuit analysis (PICA), has been introduced and developed [6], [7] for measuring delays and skews in high-speed CMOS circuits and identifying failures in microprocessors [8], [9]. It is based on the collection of hot-electron luminescence from the high-field region of MOSFETs. Hot carriers produce a weak, broad-band infrared emission [10], so that light pulses synchronous with the switching transitions are generated. Efficient measurements of such faint and fast infrared optical pulses make it possible to carry out noninvasive in-situ testing. Single transistors and complete circuits can be characterized [11]. The only prerequisite is optical access to the high field region of the transistors of the circuit under test, namely, the channel edge adjacent to the drain. It is worth stressing that both ac and dc measurements can be performed with this technique at normal operating conditions, without requiring any extra voltage or current [12].

In previous work carried out with this technique [6]–[8], photo-multiplier tubes (PMTs) were employed to detect the luminescence. The aim of this work was to attain higher sensitivity and time resolution by exploiting a silicon photodetector, the single-photon avalanche-diode (SPAD) [13]. The experimental tests were carried out on a CMOS ring oscillator supplied by IBM. This circuit is very simple to operate, straightforward to analyze, and fast enough to make possible fairly accurate evaluation of the temporal width of the emission given the instrumental time resolution. Furthermore, it is not fully covered by metal wiring, thus allowing to measure the emission from the front side of the chip.

It is worth noting that the technique is based on a repetitive detection of the photoemission during many switching transitions of the circuit under test. Nevertheless, the time resolution obtained is better than 50 ps, which corresponds to an equivalent analog bandwidth of about 20 GHz. The fast electrical waveforms within ULSI circuits can thus be probed with high bandwidth without introducing any electrical load. It is possible not only to check the propagation of signals in digital circuits and characterize delays and skews, but also to accurately measure analog waveforms, thereby characterizing signal distortions and glitches.

II. EXPERIMENTAL SETUP

Electrons flowing through the MOSFET channel are subject to intense electrical fields and acquire high energy. Hot electrons release energy by radiating photons over a broad-band spectrum, extending beyond 1.5 eV. The emission probability is very low and is a strong function of the device voltage [10]; however, in a MOSFET’s typical switching, about one photon is emitted every 100 000 electrons crossing the channel. The emission is so faint, that detectors capable of detecting single photons must be employed [14].

While the PICA technique allows the acquisition of time-resolved images of the circuit under test by means of a PMT [6], [7], we used the SPAD detector to exploit its better timing bandwidth in localized area of the chip.

Fig. 1 shows the setup used in the experiments. A microscope objective with large numerical aperture collects photons emitted by the circuit under test; a second objective focuses them onto the SPAD detector (8 μm active area diameter). Since the collecting objective defines the chip area imaged onto the detector, we used different lenses spanning from 5X (for observing a wide area of the ring oscillator) to 50X (for single inverter analysis).

The SPAD requires low bias voltage (about 22 V compared to typically 2 kV for PMTs) and operates in Geiger-like mode.
at room temperature with low intrinsic noise (the dark-counting rate is about 300 counts/s without any cooling) [15]. The active quenching circuit (AQC) [16] ensures SPAD operation with a short, well-defined deadtime after the detection of each photon and provides a digital output pulse synchronous with the photon arrival time. A time-correlated photon counting (TCPC) apparatus [17] measures the photon arrival times with respect to a synchronization signal of the circuit under test. By collecting data over many oscillator cycles, a histogram of the photon arrival time is obtained, which gives the waveform of the luminescence pulse. The collected number of detected events must be high enough to reduce statistical fluctuations, i.e., to enhance the signal-to-noise ratio (SNR) at the level necessary for observing the waveform features with the required detail. There is a tradeoff between high accuracy and short acquisition time and the detector efficiency plays a crucial role in establishing the tradeoff level.

We tested a CMOS ring oscillator running at 73.4 MHz (13.6 ns cycle time) for a bias voltage of 5 V housed in an open ceramic DIL package. A chain of 47 inverters (including a NAND gate) is followed by an on-chip counter, which demultiplies the frequency by 32 (see Fig. 1), leading to an external frequency of 2.29 MHz. An ECL comparator regenerates the square wave signal at the counter output providing the synchronization signal.

III. SENSITIVITY AND TIME RESOLUTION

By using a five times collection objective, a wide area (with elongated shape, because of the coma due to the objective) is observed on the chip, which includes various inverters, as outlined in Fig. 2. The collected optical signal over one period includes pulses from all these inverters. Fig. 3(a) reports the measured waveform over a full period and Fig. 3(b) an expanded view of the first group of pulses. A one hour acquisition time was employed for obtaining high SNR. The collected number of detected events must be high enough to reduce statistical fluctuations, i.e., to enhance the signal-to-noise ratio (SNR) at the level necessary for observing the waveform features with the required detail. There is a tradeoff between high accuracy and short acquisition time and the detector efficiency plays a crucial role in establishing the tradeoff level.

The time resolution attained, already illustrated by Fig. 3(b), has been accurately checked. By using a 50X collection objective, the observed area of the system was restricted to a spot of a few micrometers diameter, that includes just one nMOSFET inverter of the ring oscillator, marked “1” in Fig. 2. The pulse marked “1n” in Fig. 3(a) was thus isolated; an expanded timescale of the TAC was used and 20 min acquisition time was sufficient to perform the measurement reported in Fig. 4. The waveform has a full width at half maximum (FWHM) of 50 ps. In the experiments reported in [18], the FWHM was worse by a factor of 4, and the measured pulse was practically coincident with the detector time response; therefore, the information about the true width of the optical pulse was just that it was much shorter than the instrumental resolution. In this experiment, the improvement is remarkable—the measured optical pulse is now somewhat wider than the detector time response and the true optical pulswidth can be evaluated.

The time response of the SPAD was separately measured by using picosecond laser pulses; with a gain-switched laser-diode, generating pulses at a wavelength of 833 nm with about 20 ps FWHM, a waveform with 38 ps FWHM was measured, as reported in Fig. 5. By quadratic decomposition, a 32 ps FWHM is
first estimated for the SPAD response; 39 ps FWHM is consequently evaluated for the optical pulse of the inverter. The SPAD response has favorable features for carrying out a complete deconvolution: it has a regular shape (with a Gaussian peak and an exponential tail, set in evidence by the vertical logarithmic scale in Fig. 5) and can be measured with high SNR in fairly short times. However, in order to obtain significant results by deconvolution, the luminescence data must be collected with high SNR. By means of some trials and theoretical evaluations, it was estimated that an improvement of at least a factor of 10 in SNR is necessary for obtaining more detailed information about the true waveform. This implies to increase the 20 min collection time by a factor of 100. However, extending the time to more than 33 h is practically not acceptable in circuit tests. Therefore, with the available data, a deconvolution does not add significant new information to the result obtained with the quadratic decomposition. Detectors with higher efficiency and/or better time response are required for attaining further improvements.

IV. CHARACTERIZATION OF CIRCUIT FEATURES

The ring oscillator was exploited as test bench for the capabilities of the setup in Fig. 1 for circuit characterization. Systematic features in the circuit behavior have been characterized. A longer time scale of the TAC was employed to observe all the pulses emitted by the single inverter “1” over one period of the output square wave, i.e., 435.9 ns. The nMOSFET is switched on every two round trips in the inverter chain of the ring oscillator; the corresponding 32 pulses within one period of the on-chip demultiplier are reported in Fig. 6. The nominal internal cycle time is $435.9 \text{ ns}/32 = 13.62 \text{ ns}$ and should correspond to a constant time interval between consecutive pulses. However, deviations from constant interval can be observed in the experimental data of Fig. 6, as already reported in [6]. In our case, 16 intervals shorter than the nominal value are observed in
Fig. 7. Variation of the internal cycle time of the ring oscillator as a function of the cycle number (see Fig. 6).

Fig. 8. Dependence of the internal cycle-time on the supply voltage. Data obtained with the optical technique (circles) and with output frequency measurements (crosses) are compared.

the first half-period of the output squarewave ($T_{\text{ON}}$ with output level high) followed by 16 longer ones in the second half-period ($T_{\text{OFF}}$ with output level low), as illustrated in Fig. 7. The total duration of the 16 shorter intervals (square symbols) is 215.1 ns, that of the 16 longer ones is 221.1 ns. The excellent agreement of these values with $T_{\text{ON}}$ and $T_{\text{OFF}}$ directly measured at the counter output confirms the accuracy of the optical technique in signal timing. This accuracy can also be exploited inside the integrated circuit.

The technique can be employed for investigating effects due to power supply voltage variations. The measurement of Fig. 6 was repeated with various voltage values and the mean of the internal cycle-time was computed at every voltage. The results are in perfect agreement with those obtained by measuring the output frequency, as shown in Fig. 8. From the same data set it is possible to also measure the inverter pulse duration versus supply voltage. Fig. 9 shows the results. In comparison to the internal cycle time, the behavior is remarkably different; the pulselength decreases much more steeply up to 5 V and saturates above this voltage. It is worth noting that such effects, monitored with the optical technique, can supply useful insight about power supply variations in circuit zones not accessible through electrical contacts.

Statistical features in the circuit behavior can also be investigated; in particular, some insight can be gained about noise in the circuit and time-jitter in the switching transitions. In fact, the width of the measured inverter pulse waveforms depends not only on the duration of the switching transition, but also on its jitter. This occurs because the waveform is not obtained in a single-shot measurement, but by averaging many measurements performed in a high number of repetitions of the light pulse. In measurements, such as that in Fig. 6, since for all pulses the time is measured with respect to the same instant (start of the output signal period), the fluctuations of the internal cycle time will be added in the elapsed cycles. Therefore, the measured width of the various pulses in Fig. 6 will increase progressively from pulse “1” to pulse “32”. The noise in the circuit causes the switching time of an inverter to fluctuate and the cumulative result after a number of cycles will depend on the noise autocorrelation properties. If the dominant noise in the various transitions is uncorrelated, uncorrelated time fluctuations will occur and the resulting jitter will increase as the square root of the cycle number. In contrast, correlated noise components will enhance the increase; in case of strongly correlated dominant noise, typically $1/f$ noise, the increase tends to be linear with the elapsed cycle number [20]. Various sets of measurements of pulselength versus cycle number (see Fig. 6) were carried out on different scales of the TAC. A longer time scale was used for measuring all the 32 pulses; a shorter one for observing the pulses with the highest instrumental resolution. Fig. 10 reports the data obtained in the latter case for the first 12 cycles. A linear increase of 1.24 ps/cycle is consistently verified in all the measurements and denotes that $1/f$ noise is dominant in the ring oscillator circuit.

V. CONCLUSIONS

This paper demonstrates that, by means of fast SPAD detectors, MOSFET’s luminescence pulse waveforms can be measured with 50 ps FWHM resolution (see Fig. 4) and tests can be carried out on both n- and p-channel devices (see Fig. 3). Measurements of internal signals in integrated circuits with 20 GHz equivalent analogue bandwidth are possible without interfering with the circuit operation. The experimental setup has been used for quantitatively evaluating electrical characteristics and per-
performances of a ring oscillator. Systematic (see Fig. 7) and statistical (see Fig. 10) variations of the ring cycle time have been measured and their relation to the circuit behavior has been discussed. The experimental results show that this optoelectronic technique can be a valuable tool for testing and debugging fast integrated circuits.

It is worth addressing here that, from preliminary measurements, channel length scaling at fixed supply voltage seems to enhance the photoemission because of the contribution of short-channel effects. Moreover, simulations of very scaled technologies show that lowering the voltages below 1.5 V does not appear to impair photoemission [21].

We are currently exploiting the higher efficiency of the SPAD compared to that of the PMT, above all around 0.7–0.9 μm wavelength, in backside investigation. In such a way, limitations due to many layer interconnects and bonded flip-chip packaging should be overcome.

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REFERENCES


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