Tools for contactless testing and simulation of CMOS circuits

F. Stellari \(^a\), F. Zappa \(^a, *\), S. Cova \(^a\), L. Vendrame \(^b, 1\)

\(^a\) Dipartimento di Elettronica e Informazione, Politecnico di Milano, Piazza Leonardo da Vinci 32, I-20133 Milano, Italy

\(^b\) STMicroelectronics, Central R&D, Via C. Olivetti 2, 20041 Agrate Brianza, Milano, Italy

Received 2 March 2000; received in revised form 4 December 2000

Abstract

Short channel effects in MOSFETs are responsible for time-dependent hot-carrier luminescence, synchronous with the switching transitions in CMOS circuits. We propose an optical non-invasive inspection technique for high-speed signals, based on a high sensitivity solid-state photodetector with sharp time resolution. This tool is able to probe the fast electrical waveforms propagating through ULSI circuits without electrically loading the circuit under test. The measured time resolution of 50 ps allows an equivalent analog bandwidth of about 20 GHz. From the experimental results and the luminescence characterization of single transistors, we propose a SPICE model able to foresee the photoemission in complex ULSI circuits, down to transistor level. The optical testing equipment and the SPICE modeling are valuable tools for simulation, characterization and testing of fast ULSI circuits. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

Nowadays excess delays and skews are very important factors limiting the performances of high-speed ULSI circuits, often causing system failures. As feature sizes continue to shrink and packaging becomes more complex, circuit testing at device level gets a tough problem. Electron beam testing and mechanical testing are becoming ineffective due to the decrease in metal line widths and power supply voltages [1]. Therefore, alternative methods for probing circuits at device level are urgently needed [2].

It has already been shown [3,4], that an optical inspection technique based on hot-electron luminescence can be a valuable tool for dynamic circuit testing. Since this technique does not require any electrical contact, pads, or buffering that capacitively load the circuit under test, it can be efficiently used as an in situ non-invasive testing for characterizing devices and circuits [5]. The only prerequisite is an optical access to the high-field region of the MOSFET under test, i.e. the channel edge near the drain. Previous optical techniques, like photon emission microscopy (EMMI) [6,7], do not allow the analysis of dynamic circuit behavior with time resolution of few tens of picoseconds, as in the technique we present.

By imaging small areas of the chip under test onto a fast photodetector, it is possible to measure the time of flight of photons emitted by the device. Although this is only a probe for static testing, it is possible to perform dynamic testing by using a high speed camera. The emitted photons are detected with a fast photodetector, and the image is acquired with a high speed camera. The only prerequisite is an optical access to the high-field region of the MOSFET under test, i.e. the channel edge near the drain. Previous optical techniques, like photon emission microscopy (EMMI) [6,7], do not allow the analysis of dynamic circuit behavior with time resolution of few tens of picoseconds, as in the technique we present.

Since the luminescence coming from the device under test is very faint [10], instead of standard photomultiplier tubes (PMT) and CCD we employed a solid-state detector known as a single photon avalanche diode (SPAD) with high sensitivity and very low intrinsic time jitter (50 ps full width at half maximum (FWHM)) [11].

We characterized the emission intensity of different n-MOSFETs at different biasing condition, and we quantitatively linked the measured optical emission to the

---

*Corresponding author. Tel.: +39-2-23996149; fax: +39-2-2367604.
E-mail addresses: franco.zappa@elet.polimi.it (F. Zappa), loris.vendrame@st.com (L. Vendrame).
\(^1\) Tel.: +39-39-6036818.
current and voltage waveforms, by studying the physics underlying the luminescence. In order to provide a valuable simulation tool for ULSI circuit analysis both at design and testing levels, we developed an analytical model and a SPICE part able to foresee the MOSFET photoemission. By comparing the simulated and measured optical waveforms, it could be possible to identify failures and fix errors in schematics and layouts.

2. Detector requirements

Electrons flowing through the MOSFET channel experience an intense electrical field that heats them to high energies. As shown in Fig. 1, in the channel region near the drain these hot electrons can generate two distinct processes: (i) the emission of near-infrared photons with energy of about 1.5 eV, or (ii) the generation of electron–hole pairs by impact ionization.

The light intensity has been estimated elsewhere [10]: a typical emission spectral density per each carrier flowing through the channel is \( S_e = 10^7 \) ph/eV/s around 1 eV. Let us consider for instance a switching transition of MOSFET with a hot-carrier region length \( L_{h} = 10 \) nm, a drain current \( I_d = 10 \) µA and a carrier saturated velocity \( v_s = 10^7 \) cm/s. Assuming carriers velocity saturation near the drain, the number of electrons that acquire enough energy to produce luminescence is about:

\[
N_e = \frac{L_h I_d}{q v_s} \approx 6.
\]  

Assuming that the emission bandwidth is \( B = 0.1 \) eV around 1 eV (i.e. wavelengths in the 1.18–1.3 µm range) and considering a switching transition of \( T_S = 200 \) ps, from Eq. (1) we can estimate the number \( N_{ph} \) of photons emitted per switching transition:

\[
N_{ph} = S_e B T_S N_e \approx 10^{-3} \text{ ph/switching.} \tag{2}
\]

Since a reasonable collection efficiency of the optical system is \( \gamma_{opt} = 4\% \) (see Section 3), it follows that the number \( N = \gamma_{opt} N_{ph} \) of photons reaching the detector is very low, about \( 4 \times 10^{-5} \) ph/switching. In order to detect such a weak emission, we used silicon SPADs [11] with 10 µm diameter active area (see Fig. 2) and 50 ps FWHM time resolution.

Even if the near-infrared quantum efficiency is not very high \( (\eta_D < 1\%) \), silicon detectors have been preferred to germanium ones due to their lower noise, measured by the dark counting rate \( n_B \), i.e. the number of spurious ignitions caused by thermal generation instead of photon absorption. Commercially available germanium SPADs have a higher dark counting rate (much greater than 100 kcps, counts per second) [12] compared with silicon detectors (60 cps).

The rate of photons detected by the SPAD is the product of the number of photons arriving onto the detector per switching transition, \( N \), times the quantum detection efficiency, \( \eta_D \), and the number \( f_R T_m \) of switching transitions of the device under test, in the measure time \( T_m \):

\[
S = N \eta_D f_R T_m. \tag{3}
\]

Assuming a faint signal, the noise is mainly due to the dark counting rate, \( n_B \), and therefore the signal to noise ratio (SNR) is:

\[
\text{SNR} = \frac{N \eta_D f_R T_m}{\sqrt{n_B T_m}}. \tag{4}
\]

In order to guarantee a minimum SNR = 1 with an acquisition time \( T_m = 10 \) min and a switching rate \( f_R = 10 \) MHz, the limit is \( n_B < 9600 \) cps. Thanks to even low noise of our detector \( (n_B = 60 \) cps), the measure time \( T_m \) can be reduced down to few seconds.

3. Measurement technique

As shown in Fig. 3 a microscope objective, with large numerical aperture (0.65), collects the photons isotropically emitted by the device under test, while another objective focuses them onto the SPAD. By properly

Fig. 1. Hot electrons flowing through the MOSFET channel can generate near-infrared photons or electron–hole couples.

Fig. 2. In a SPAD, a p+ diffusion defines the sensitive region, where the absorption of a single photon can trigger an avalanche current pulse.
taking into account the objective numerical aperture (collection efficiency of 0.93%), the reflections at the silicon–air interfaces (30%), and considering mirror and objective losses (15% each), the total transmission efficiency is estimated to be:

$$\gamma_{\text{opt}} \approx 0.93\%(1 - 30\%)(1 - 15\%) \approx 4\%.$$

(5)

The SPAD is reverse biased above its breakdown voltage and each photon absorbed in the depletion zone can cause an avalanche ignition that produces a detectable current of some mA. The active quenching circuit (AQC), in Fig. 4, senses the current through the resistor $R_s$, provides a suitable digital output pulse, synchronous with the photon arrival time, quenches the avalanche current and, after a constant delay, resets the SPAD for the next detection [13]. A time to amplitude converter (TAC) and a multi-channel analyzer (MCA) collect the photon arrival times and reconstruct the histogram corresponding to the shape of the optical waveform, as in standard time correlated photon counting measurements [14].

4. MOSFET characterization

We characterized the emission intensity of different n-MOSFETs with channel lengths ranging from 0.4 to 1 μm, substrate doping of $10^{16}$ cm$^{-3}$, and oxide thickness...
of 120 Å. Fig. 5 shows the measured number of emitted photons as a function of the gate and drain voltages for the 0.5 μm MOSFET.

As can be seen in Fig. 5, the luminescence intensity depends on the operating conditions of the transistor, therefore optical measurements can be a valuable technique for back estimating voltages and currents in transistors.

In order to quantitatively link the measured optical emission to the current and voltage waveforms in the device, we studied the physics underlying the luminescence. The optical emission depends on two factors: (i) the number of electrons flowing through the MOSFET channel and (ii) the probability of each electron to emit a photon.

To evaluate the first term, the source current $I_s$ must be used instead of the drain current, because the latter includes also the bulk current contribution due to impact ionization: $|I_D| = |I_S| + |I_B|$. On the contrary, secondary electrons generated by impact ionization cannot acquire enough energy to contribute to the photon emission process, therefore the emission intensity is proportional to $I_s$.

The emission probability depends on the electrical field intensity along the channel. Since the shape of the field is almost constant at a given channel length [15], the probability can be linked to the maximum electrical field $F_{max}$ which is a function of the bias conditions [16]

$$F_{max} = \frac{V_{DS} - V_{DS_{sat}}(V_{GS})}{l}.$$  \hspace{1cm} (6)

The equivalent length $l$ can be evaluated from technological parameters, while the dependence of $V_{DS_{sat}}$ on $V_{GS}$ can be calculated by constructing the locus of constant $I_b/I_s$ ratio as proposed in Ref. [17]. In Fig. 6, the rate of emitted photons is normalized to $I_s/q$ ($q$ is the electron charge) and plotted versus the difference $V_{DS} - V_{DS_{sat}}$. All curves superimpose very well for many orders of magnitude, thus confirming that secondary electrons do not contribute to the emission process.

The emission probability can be inferred if we suppose that the emission process depends on the electric field $F$ as $e^{-C/F}$ [17], where $C$ is an appropriate constant. It is interesting to observe that the same dependence
applies to the impact ionization coefficient accounting for the bulk current. By integrating the emission coefficient in the high-field region near the drain and using Eq. (6), we obtain the rate of emitted photons:

\[ N_{ph} = A \frac{I_S}{q} (V_{DS} - V_{DSSat}) e^{-(B/(V_{DS} - V_{DSSat}))}, \]  

(7)

where \( A \) and \( B \) are two fitting coefficients, accounting for the MOSFET dimensions and the light collection efficiency of the optical setup. Fig. 6 shows the good agreement of Eq. (7) with experimental data, by choosing \( A = 1.1 \times 10^{-11} \text{ V}^{-1} \) and \( B = 21.6 \text{ V} \).

5. Analog waveforms acquisition

Beyond static characterization, it is important to quantitatively investigate signal dynamics, on both amplitudes (digital levels, current and voltage analog values, reflection steps, glitches, etc.) and time scale (measuring propagation delays, transition durations, clock skews, etc.). In order to investigate the analog performance of the optical technique, we drove a packaged CMOS receiver via a 50 Ω coaxial cable (see Fig. 7), with no matching input resistance in order to cause waveform reflections. We applied a 100 kHz digital stream with 700 ns pulse durations and, by focusing the optical setup onto the receiver input transistor, we acquired the waveform shown in Fig. 8 in a 10 min measurement.

The steps in Fig. 8 correspond to twice the transit time \((2 \times 100 \text{ ns})\) along the transmission line, as proven by a crosscheck inspection with a standard oscilloscope probe (1 MΩ, 10 pF). Moreover, the optical inspection technique allowed the detection of two fast glitches, which could not be detected by the scope, because of the capacitive loading.

Therefore the optical testing offers the chance to quantitatively estimate parameters like the voltage signal amplitudes with good resolution, depending on desired SNR. For instance, by smoothing the waveform in Fig. 8 and using the transfer characteristic (voltage vs.

emission intensity) previously acquired (Fig. 9), it was possible to evaluate the steps height and compute the line reflection coefficient \( \Gamma_S = -\Delta V_2/\Delta V_1 = -0.78 \) at the

![Fig. 7. A packaged CMOS receiver is connected to a remote pulse generator via a coaxial line with no termination, thus causing reflections.](image)

![Fig. 8. Optical pulse measured from the CMOS receiver input transistor: steps and glitches are due to reflections.](image)

![Fig. 9. Comparison of the simulated luminescence (lines) with the experimental data (dots).](image)
remote driver side and its output resistance $R_s = (1+T_s)/(1-T_s)Z_0 = 6.2 \ \Omega$.

6. SPICE modeling

The next goal was to offer a simulation tool able to foresee the luminescence. Our idea was to implement in SPICE the analytical models of the luminescence as a function of the MOSFET bias points. We used a basic BSIM SPICE model that does not implement any body current model and we added a voltage output pin for the photoemission intensity $N_{ph}$ (inset in Fig. 9 and the bulk current generator (inset in Fig. 10). The former value is computed from Eq. (7) with a simple interpolation of the $V_{DS, sat}$ expression derived from [17]. Also for the latter we used an expression similar to Eq. (7), since electron–hole pair generation depends on the same hot-electron distribution in the MOSFET channel.

The results for the simulated luminescence (Fig. 9) and the current–voltage characteristics (Fig. 11) satisfactorily match the experimental data. This proves that the proposed SPICE modeling together with the optical testing technique is a combined software and hardware tool, able to quantitatively foresee, test and check the behavior of ULSI circuits.

7. Digital circuit characterization

Both luminescence measurement and simulation can be performed also in complex circuits for studying signal waveforms dynamics [18]. In order to prove the capability of detecting fast switching transitions and measuring delays, we tested some ring oscillators. We collected the luminescence coming from n-MOSFETs in the 25-stages ring oscillator shown in Fig. 12, working at $f_{osc} = 14.3 \ \text{MHz}$. The measurement lasted 5 min for each inverter that was individually measured. From Fig. 13 we estimate in 1.4 ns the propagation delay between transistors as half the delay between even (odd) n-MOSFETs and in 800 ps FWHM the switching duration for each commutation. The latter is well above the intrinsic 50 ps time resolution of the SPAD (also shown in Fig. 13), which allows analog bandwidth of about 20 GHz.

Fig. 14 shows a draft of the ring oscillator schematic of Fig. 12 with the proposed transistor parts. Fig. 15
can be a valid alternative to traditional methods for probing fast electrical waveforms propagating through integrated circuits. The very sharp time resolution of the SPAD allows a 20 GHz analog bandwidth on repetitive measurements. The high sensitivity of the detector guarantees fine amplitude resolution in the analog waveforms acquisition.

Moreover we developed a suitable SPICE model able to foresee the photoemission intensity. The availability of highly sensitive SPADs and the refinement of the optical setup will open the way to the measurement of fast luminescence also from the backside of the chip. This will allow the characterization of very dense ULSI chips, where metal and polysilicon layers usually screen the luminescence from the front or where special packaging techniques (i.e. ball grid array) do not allow an easy access from the top.

Acknowledgements

The authors want to acknowledge Luciano Pallaro for accurate micromechanical manufacturing of many parts of the optical setup.

References