Implementation of TRE systems into Emission Microscopes

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Abstract

Time-Resolved photon Emission (TRE) has the potential to identify faults by analysing the luminescence emission, as a function of time. TRE detectors provide time capabilities, but they have the disadvantage to be a single-point measurement, with no possibility to spatially map the luminescence emissions from the chip. In order to first localize the luminescence origin (e.g. a switching transistors or a faulty device within a chip), it is interesting to couple TRE equipments (\textit{i.e.} time information) with light emission microscopes (\textit{i.e.} spatial information).

In this paper, we present a quantitative comparison of various commercially-available TRE detectors and photon counting electronic modules. From the analysis of the best solution, we propose a cost effective solution for the implementation of a TRE detector into a commercial emission microscope, with no hardware modifications.

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1. Introduction

Emission Microscopes are currently used to identify and investigate physical defects and faulty behaviours within microelectronic devices and circuits. The exploited principle is the luminescence emitted by hot-carriers accelerated by the high electric fields inside individual transistors [1].

A main advantage of Emission Microscopy (EMMI) technique is that it is completely non-invasive, since it requires no probes and no laser or electrical excitation, apart from the normal operating electrical signals.

The commonly used detectors in such microscopes are two-dimensional imaging sensors, like CCDs, HgCdTe arrays, PMTs, InGaAs arrays, which provide a spatial 2D image of the luminescence. Both the position of the emission and its intensity can be used to gain better insight into the operating conditions of the chip under test. Further useful information can be also extracted from the emission spectra [2].

Information about the spatial position of luminescence spots is important to precisely localize emission sources. However, in order to identify anomalous behaviours and faulty devices, timing information must be investigated.

Time-Resolved photon Emission (TRE) techniques can acquire the time dependence of luminescence, by means of single point detectors. PhotoMultiplier Tubes (PMTs) have the typical disadvantages of vacuum tubes and high voltage operating levels. Avalanche Photodiodes are solid-state detectors operated in the linear multiplying regime in order to provide an internal gain of few hundreds at best. Instead, Silicon, Germanium or III-V Single-Photon Avalanche Diodes (SPADs) [3] are Geiger-like counters, able to count single photons and provide the photon arrival time with picosecond resolution. Also, other detectors like the SSPD [4] can exploit single-photon sensitivity, but they are usually bulky and very expensive.
Since TRE detectors do not provide spatial information about the collected luminescence. It is interesting to complement TRE equipments with emission microscopes: first to localize the emission source (e.g. a switching transistor) and then to reconstruct the luminescence waveform. To this aim, the right combination of single-photon detectors and timing electronics is of the utmost importance.

In the following, we will go through an in-depth comparison of different commercial TRE detectors and photon counting electronic boards. Of course, the review of all key parameters must be balanced with cost and ease of use to retain the best solution for integrating a TRE module into an available emission microscope. From the experimental characterization of different combinations, we will present the best practical implementation of a cost effective solution of a TRE detector into a commercial Hamamatsu PHEMOS emission microscope, with no hardware modifications. All results are compared with existing commercial TRE systems.

2. TRE Principle

In semiconductor devices, the generation of energetic hot-carriers under high electric fields, leads to spontaneous photon emission [5], [6], [7], [8]. Such conditions are mostly evident within the MOS transistor channel, near the drain, as shown in Fig. 1. The emission rate depends on the electric field (linked to the drain-source voltage) and the number of carriers flowing through the channel (i.e. the source current). The photon emission rate, $N_{PH}$, can be expressed as a function of drain voltage, $V_{DS}$, the source current, $I_S$, and the saturation drain voltage, $V_{DSat}$, as in the following equation [11]:

$$N_{PH} = A \frac{I_S}{q} (V_{DS} - V_{DSat}) \exp \left( \frac{-B}{V_{DS} - V_{DSat}} \right)$$

The two A and B coefficients depend on process parameters of the DUT (doping profiled, oxide thickness, etc.) and optical collection efficiency of the experimental apparatus. The emission is maximized at high electric fields and large current levels, that is mostly during the switching transition of digital gates, as proved by the simulation shown in Fig. 2.

3. Detector performance parameters

The key parameters of TRE detectors are detection efficiency, spectrum sensitivity, time jitter, timing accuracy, intrinsic noise, and cost. Detection efficiency gives the probability that a photon entering the sensor’s active area be detected and captured by the following electronics. Depending on the wavelength of the impinging photon, detection efficiency varies, thus yielding to not constant spectrum sensitivity. The current build-up in the detector is used to signal the photon arrival time and must be measured with the best timing resolution, i.e. with the minimum time jitter. Unfortunately, spurious ignitions of the detector (e.g. caused by thermal generations, trapping phenomena, leakage currents), not due to signal photons, represent the detector intrinsic noise and yield acquisitions uncorrelated with the desired signal waveform.

The cost of TRE detectors can span from few hundreds of Euros for planar CMOS-like SPADs [14] or some thousands of euros for custom reach-through SPADs [12], up to some millions of euros for developmental single-photon detectors, like superconducting SSPD [15].
For photon counting electronics, the important requirements are time jitter, maximum counting rate, maximum time scale, minimum time bin, and cost. The time jitter must be the lowest in order not to spoil the timing resolution of the TRE detector; good performances are below tens of picoseconds. High maximum counting rates allow the acquisition of single-photons at fast rates, thus speeding up the measurements. High maximum time scale over minimum time bin ratio marks instruments able to acquire long-lasting waveforms with very high resolution. Concerning the cost of photon-counting board it usually spans beyond some 10,000 euros.

4. Practical TRE systems

4.1 Detectors

We used different detectors and we measured their performances straight on field, by acquiring the luminescence emitted by a ring-oscillator running at 150MHz. We began the investigation of a Super S25 PMT from Quantar [9]. Then we used a commercial photon counting module by PerkinElmer [12], based on a silicon APD operated in Geiger-mode. Both detectors were installed inside an OPTICA tool from NPTsoft [13]. Finally we used a single-photon detection module based on silicon SPAD produced by Politecnico di Milano (PoliMI) [14]. Such module was plugged into an eyepiece of a PHEMOS emission microscope (as it will be shown in Fig. 8).

With all three detectors, we acquired the time-resolved luminescence waveforms by means of two different electronic boards: a Becker&Hickl SPC-630 board [16], plugged into a PCI slot of a personal computer; and a custom Time Measurement Unit (TMU) designed by NPTsoft.

Fig. 3, Fig. 4 and Fig. 5 show the time-resolved acquisitions obtained by the three detectors in 10 minutes, when using the Becker&Hickl timing board, with a time bin set to 12ps. As it can be seen from immediate and quantitative comparisons, we can extract important insights. The dark counting rate is highest with the Super S25 PMT (100 counts in each 12ps-time bin after 10min-acquisition) and lowest with the SPAD detector (about 1 count on average). The value of PerkinElmer detector cannot be assessed due to the long decaying tails after the peaks that overlap each other. Anyhow, PerkinElmer and PoliMI SPADs noise level are almost comparable.
Tab. 1: Summary of key parameters of TRE detectors (from datasheets).

<table>
<thead>
<tr>
<th></th>
<th>PoliMI Si-SPAD</th>
<th>PerkinElmer Si-APD</th>
<th>Mepsiron Super-S25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection efficiency (@ 900nm)</td>
<td>3%</td>
<td>34%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Spectrum sensitivity</td>
<td>Up to 1100nm</td>
<td>Up to 1100nm</td>
<td>Up to 1000nm</td>
</tr>
<tr>
<td>Timing jitter (FWHM)</td>
<td>35ps</td>
<td>550ps</td>
<td>150ps</td>
</tr>
<tr>
<td>Timing accuracy</td>
<td>&lt;2ps</td>
<td>&lt;6ps</td>
<td>±15ps</td>
</tr>
<tr>
<td>Intrinsic noise (Dark counting rate)</td>
<td>&lt;50cps</td>
<td>25cps</td>
<td>600cps</td>
</tr>
<tr>
<td>Cost</td>
<td>Low (Soon on market)</td>
<td>Medium</td>
<td>High</td>
</tr>
</tbody>
</table>

Tab. 2: Summary of most important data acquired during our field evaluation, with the three detectors.

<table>
<thead>
<tr>
<th></th>
<th>PoliMI Si-SPAD</th>
<th>PerkinElmer Si-APD</th>
<th>Mepsiron Super-S25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum (counts)</td>
<td>60</td>
<td>285</td>
<td>675</td>
</tr>
<tr>
<td>FWHM - Best (ps)</td>
<td>68</td>
<td>660</td>
<td>120</td>
</tr>
<tr>
<td>FWHM - Mean (ps)</td>
<td>77</td>
<td>745</td>
<td>129</td>
</tr>
<tr>
<td>Background level (counts)</td>
<td>1</td>
<td>8</td>
<td>100</td>
</tr>
<tr>
<td>Total counts (counts)</td>
<td>9,604</td>
<td>252,958</td>
<td>510,239</td>
</tr>
</tbody>
</table>

The time jitter of the TRE set-up is of the utmost importance, since it yields the ultimate limit in resolving luminescence peaks and switching delays of ultra high speed circuits [17]. Again from Fig. 5, it is easy to notice that the best timing resolution is achieved with the SPAD detector (about 70ps Full-Width at Half Maximum). Instead PerkinElmer shows a poor resolution of 660ps, in spite of the much better 550ps-FWHM reported in the data-sheet. The Mepsiron detector has intermediate performance, with 120ps-FWHM. Tab. 1 lists the key parameters for the compared TRE detectors, taken from datasheets. Tab. 2 reports our experimental measurements.

Concerning detection efficiency, Fig. 6 shows the intrinsic spectral efficiency of the three detectors. The PerkinElmer APD has the highest efficiency, thanks to the wide depleted region of the photodiode. PoliMI Si-SPAD has a thin depleted region, hence a lower detection efficiency in the long wavelength range, compared to PerkinElmer APD. Finally, the Mepsiron detector has a flat spectral response, but shows the poorest efficiency.

Regarding the timing performances, PoliMI Si-SPAD overwhelms the other two sensors, thanks to its intrinsic structure that is operated at high electric fields and with limited active area (less than 10µm-diameter). Finally, the dark counting rate of PoliMI Si-SPAD and PerkinElmer Si-APD are comparable and lower than that of Mepsiron PMT.

Fig. 6: Detection efficiencies of the three different detectors employed in our evaluations.

Fig. 7: Detection efficiencies of various photodetectors used in emission microscopes and TRE apparatus.
4.2 Optical system

For our evaluation we performed acquisition on the same device using the OPTICA system (PICA Mepsicron detector and SiAPD) and a Phemos 1000 (PolimiSPAD). To also compare the time detection electronics, we used both OPTICA TMU board and SPC-630 card for all 3 detectors. Since the three detectors are installed into two different microscopes. However, a qualitative comparison of the two optical systems points out that PerkinElmer Si-APD and Mepsicron PMT take advantage of a better optical path, with smaller losses than those experienced by Polimi SI-SPAD module, mounted into a standard eyepiece of the microscope, instead of a dedicated optical port. It is very difficult to precisely compare the overall efficiency of the three detection set-ups.

For comparison, Fig. 7 reports the detection efficiency of other detectors used in TRE equipments and emission microscopes, namely SSPD |8|, Ge SPAD |9|, InGaAs APD |10|, MCT |11|, and CCD |12|. Some of them have spectral response that best fit the emission spectrum of integrated circuits. Their drawbacks are higher costs and more complex operating conditions.

4.3 Timing board

For all the measurements, we used two different timing boards, SPC-630 card and TMU board. The former has better timing performances, with very limited (7ps) time jitter, while the latter benefits from the possibility to use very long time scales with a limited time bin (2.5ps).

In our opinion, TMU board showed high benefit for long test pattern acquisition, but the dead time (minimum time for the electronics to acquire a next photon) is very large. As a result, photons may be lost at high levels of luminescence emission. On other hand, the SPC-630 can reach very high counting rates. Unfortunately, for long time scales the timing resolution of SPC-630 lowers.

5. Implementation of TRE in a PHemOS

Fig. 8 shows the proposed experimental set-up that, after the comparisons, shows the best performances. It is a PHemOS emission microscope, with the DUT mounted on the chuck and the Polimi SI-SPAD module plugged into an eyepiece of the microscope.

6. Perspectives

Fig. 8: Implementation of the Polimi SPAD detection module (shown within a circle) into a PHemOS 1000.

The advantages of this implementation are that it needs no hardware modification of the original Phemos 1000 emission microscope. In fact, the module is simply plugged into the eyepiece port. The only drawback is that the transmission losses along the optical path of the eyepieces are greater than those of the light path toward the CCD camera of Phemos. However, the low dark counting rate, the remarkable timing capability, and the good detection efficiency of Polimi SI-SPAD allow the collection of luminescence waveforms with high signal-to-noise ratio (see Fig. 5).

Here are our considerations, after the comparisons.

- **Microscope.** TRE detectors can be implemented into standard microscopes. Thanks to the high sensitivity of Polimi SPAD, such detector can be easily added into commercial emission microscopes. We chose a Phemos system available in our lab.
- **TRE detector integration.** OPTICA system is based on a platform equipped with three ports that, for instance, makes it possible to simultaneously host a PICA Mepsicron and a Si-APD. An interesting possibility could be to implement the Polimi SPAD in place of the fiber-mounted Si-APD.
- **Electronic timing board.** Among commercial solutions, we chose the SPC-630 card, which offers
good flexibility for TRE implementation and offers high timing performances at an affordable cost. Another reason is software integration, which makes it possible to easily acquire data and quickly manipulate the time-resolved waveforms.

- Detector choice. Among detectors, PoliMI SPAD is the best choice for cost and performance. From our standpoint, its high timing resolution is an optimal complement to the high efficiency CCD camera.

7. Conclusions

We made a quick review of the TRE principles. Then we identified the detector key parameters: detection sensitivity, quantum efficiency, time jitter, noise, and cost. From experimental characterizations, we chose the best compromise. Finally, by using a commercially-available photon counting electronic card, we implemented this cost effective solution into a standard emission microscope: a Hamamatsu Phemos 1000. The remarkable results prove that a proper combination of a TRE system and an Emission Microscope can provide both spatially-resolved maps and time-resolved waveforms of the luminescence emitted by integrated circuits and devices. The resulting apparatus is a powerful tool for non-invasive testing and debugging in modern semiconductor industry. We are currently working on non silicon TRE detectors to cover light emission beyond 1μm.

References


