Novel NIR camera with extended sensitivity and low noise for photon emission microscopy of VLSI circuits

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Abstract

This work presents a new photon emission microscopy camera prototype for the acquisition of intrinsic light emitted from VLSI circuits during their normal operation. This novel camera was designed to be sensitive to longer wavelengths in order to maximize the signal intensities from modern VLSI chips which are characterized by a red shift in the intrinsic emission spectrum. In this paper, we will characterize the performance of the camera using 32 nm and 22 nm SOI chips. The novel camera is able to collect emission images with the circuit under test operating at a supply voltage down to 0.5 V, exceeding the performance of a state-of-the-art InGaAs camera.

Introduction

Backside Photon Emission Microscopy (PEM) is commonly used for circuit diagnostics and analysis of VLSI chips. Time-integrated emission images may be used for many different applications: to localize anomalous emission spots associated with failure mechanisms, to acquire logic state maps for circuit debugging [1], to characterize chip variability for yield improvement [2], to measure power supply voltage droops [3], and more recently for circuit security applications [4]. One of the main advantages of PEM technique is the fact that it is a completely non-invasive technique: it does not alter or damage the circuit under test.

However, with the continuous shrinking of integrated circuits, both in terms of power supply voltage and feature size, the detection of the intrinsic photon emission is becoming challenging. Reducing the operating voltage of the circuitry leads to much fainter signal intensities in time-integrated emission images, that decreases as the exponential of the reciprocal applied voltage [3][5]. Moreover, recent work showed a red-shift of the emission spectrum towards longer wavelengths [6]. Therefore, conventional detectors used for emission microscopy, such as Si-CCDs or even InGaAs cameras, are no longer a good option, given that they are not able to detect a significant portion of the emission spectrum due to their low cutoff wavelengths.

This paper presents the characterization of a new time-integrated detector prototype with extended sensitivity and low noise. This allows one to acquire time-integrated images even at very low voltages – i.e. $V_{dd} = 0.5 \text{ V}$ – within a few minutes. Performances of this new camera are compared with those of a state-of-the-art liquid nitrogen ($\text{LN}_2$) cooled InGaAs camera, showing superior capabilities that can be exploited to test future technologies of integrated circuits.

Experimental Setup

Fig. 1 shows our experimental setup with the novel PEM camera (DiamondBack eXtended [7], DBX, developed by DCG Systems) mounted on a Meridian-IV tool. The 1024 x 1024 pixel focal plane array is made of an extended infrared material with sensitivity up to 2000 nm. This allows the detection of the significant part of the VLSI circuits.
emission spectrum that other cameras – e.g. InGaAs detectors with $\lambda_{\text{cutoff}} < 1600 \text{ nm}$ – missed. The DBX camera is cryogenically cooled with LN$_2$ ($\sim 77 \text{ K}$) to reduce noise and provide an adequate thermal shield. Inside the dewar, a set of Short-Pass (SP) filters with different cutoff wavelengths $\lambda_{\text{cutoff}}$ can be used to set an upper limit to the incoming light spectrum. Different lenses can also be used according to the resolution desired for the PEM image: starting from a macro 1X lens, passing through 20X and 50X, to a 350X Solid Immersion Lens (SIL). The board with the Device Under Test (DUT) is mounted on top of the Meridian-IV stage and connected to power supplies and pulse generator.

**DBX Characterization**

The new camera was first tested in combination with the different short-pass filters in order to optimize the cutoff wavelength and obtain the best SNR in time-integrated images acquired from VLSI circuits. Furthermore, we were able to demonstrate that the camera is sensitive to emission signals for circuit power supply voltages down to 0.5 V using a 32 nm SOI testchip. We also directly compared the performance of the new camera with that of a state-of-the-art InGaAs camera. Finally we showed that, with this PEM camera a nice emission image can be acquired from a 22 nm SOI chip in only 10 seconds.

**Time-integrated images with different short-pass filters**

As a first characterization we checked that the emission signal intensity acquired with PEM cameras gets stronger when the sensitivity of the detector is extended to longer wavelengths. To prove that, we used the DBX camera in combination with the different short-pass filters and acquired 2D images from a 32 nm SOI testchip using the high Numerical Aperture (NA) SIL. In particular, the DUT had an inverter chain consisting of 7 stages, with 5 x 650 nm n-FETs (bottom inverter chain in Fig. 3). Time-integrated emission images were acquired for $T_{\text{acq}} = 30 \text{ s}$ from the chip switching at $f = 100 \text{ MHz}$. Fig. 2 shows the 2D images (first row), together with the 3D plot (second row) of the emission intensity and the profile along the n-FETs of the inverter chain (third row). Note that the first emission spot corresponds to a device in the driver section (see Fig. 3). As expected, the signal intensity increases when the extended spectral sensitivity of the DBX camera is exploited. One can also observe a significant change of emission intensity depending on the particular gate along the inverter line. This is due to random process variations affecting the transistor thresholds in this early version of the testchip, and such small variations are amplified in emission images given the exponential dependence of the emission intensity on the voltage.

**Sensitivity at very low voltage**

The same testchip, consisting of inverter chains with FETs of different sizes and spacing (Fig. 3a), was used to test the sensitivity of the new camera down to very low voltages. To this aim we used the SP filter that optimizes the SNR, i.e. the one with $\lambda_{\text{cutoff}} = 1800 \text{ nm}$ (more details on SNR optimization in the following section), and acquired the emission from the chip running at a very low power supply voltage $V_{\text{dd}} = 0.5 \text{ V}$ using the SIL for 10 minutes. Note from Fig. 3b how we are

![Figure 2: Dependence of the detected intrinsic emission intensity from the chip on the cutoff wavelength of the short-pass filter used in combination with the DBX camera and the SIL lens. 2D images, 3D plot, and emission profile along the dashed white lined and gray planes are shown in the first, second and third row respectively.](image-url)
Figure 3: a) Layout of the 32 nm SOI testchip used for DBX characterization, consisting of 10 inverter chains with different FETs’ dimensions and spacing between one inverter stage and the following one. b) PEM image acquired from the testchip running at $V_{dd} = 0.5$ V, with only the two top and bottom inverter chains powered on, using the DBX camera in combination with the 1800 nm short-pass filter. The image was acquired using the SIL for $T_{acq} = 600$ s. Note how emission can be detected also from the smaller devices.

able to detect the emission even from the smaller devices (single finger FETs 208 nm wide) in the testchip.

**DBX vs. InGaAs camera comparison**

The new camera performances were also compared to those of a state-of-the-art InGaAs camera by acquiring emission images from the testchip in Fig. 3a, running at different operating voltages (i.e. from 1.2 V down to 0.5 V). To obtain a fair comparison of the two cameras, we used the same Meridian-IV optical system and the PEM images were acquired through the same SIL.

For the purpose of this analysis, we define SNR as the ratio between the emission intensity signal and the noise of the measurement. In particular, the signal was defined as the mean of the emission intensity collected by the camera pixels from the second of the 7 $n$-FETs of the inverter chain (Fig. 4) minus the mean of the intensity in the noise area. The noise was defined as the standard deviation of the pixel intensities in an area of the same size of the previous one, but at a location far from the Region Of Interest (ROI) defined for the emission, where no emission is detected (Fig. 4).

Fig. 5 shows the results in terms of emission intensity signal (a), noise (b) and SNR (c) for the DBX camera, at different voltages and with different short-pass filters. All the images were acquired using a fixed acquisition time of 60 seconds to simplify the comparison and rule out any acquisition time non-linearity. As already shown in Fig. 2, the emission signal intensity detected by the DBX camera improves when its

Figure 4: Example of PEM image acquired for the camera comparison and definition of the Regions Of Interest (ROIs) for emission and noise for signal-to-noise ratio calculation.
Figure 5: Emission intensity signal (a), noise standard deviation (b) and resulting signal-to-noise ratio (c) obtained with the DBX camera and the SIL lens at different $V_{dd}$ and using the different short-pass filters. Both the signal and the noise increase using longer wavelength filters, but the SNR shows an optimum when the SP1800 filter is used. All the measurements were acquired using $T_{acq} = 60$ s.

Figure 6: Emission intensity signal (a), noise standard deviation (b) and resulting signal-to-noise ratio (c) obtained with the InGaAs camera and the SIL lens at different $V_{dd}$ and using different acquisition times. Signal, noise and SNR increase using longer acquisition times. At high $V_{dd}$ the camera saturates if the acquisition time is too long.
terms of emission signal, noise and SNR are summarized in Fig. 6a, 6b and 6c, respectively. As expected, all these quantities scale with the acquisition time. Note also how the acquisition time is limited by the saturation of the camera at high voltages (Fig. 6a).

Fig. 7 shows a comparison of the performances achieved with the new DBX and the InGaAs camera. Here we show only the results obtained with the DBX with two of the four short-pass filters, i.e. SP1600 and SP1800. The former is the one that mimics the InGaAs cutoff, while the latter is the one that optimizes the SNR.

The DBX with SP1600 (black solid line in Fig. 7) is less sensitive than the InGaAs camera with the same acquisition time (green dashed line in Fig. 7), also because of reduced transmission caused by the presence of the filter in front of the DBX camera. However, the significantly lower noise of the DBX allows for an SNR which is about 2 times better than that of the InGaAs camera over the entire $V_{dd}$ range (see Table 1). The SNR achieved with the DBX combined with the 1600 nm short-pass filter is actually comparable with that obtained with the InGaAs camera at $T_{acq} = 300$ s (blue dashed line in Fig. 7), thus achieving the same SNR five times faster.

If, instead, we compare the best performances obtained with the DBX – i.e. with the SP1800 (purple solid line in Fig. 7) – with those obtained with the InGaAs camera, the SNR improvement in comparison to the InGaAs measurement with the same acquisition time (green dashed line in Fig. 7) is even

### Table 1: Values of the signal-to-noise ratio for the InGaAs and DBX cameras. The improvement factor in SNR of the DBX with respect to the InGaAs camera is also highlighted.

<table>
<thead>
<tr>
<th>$V_{dd}$ (V)</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
<th>1.0</th>
<th>1.1</th>
<th>1.2</th>
</tr>
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<tbody>
<tr>
<td>InGaAs, $T_{acq} = 60$ s</td>
<td>SNR</td>
<td>0.6</td>
<td>3.7</td>
<td>12.5</td>
<td>34.7</td>
<td>84.3</td>
<td>191.2</td>
</tr>
<tr>
<td>InGaAs, $T_{acq} = 300$ s</td>
<td>SNR</td>
<td>1.7</td>
<td>8.0</td>
<td>27.5</td>
<td>87.3</td>
<td>192.3</td>
<td>418.0</td>
</tr>
<tr>
<td>DBX, SP1600, $T_{acq} = 60$ s</td>
<td>SNR</td>
<td>Improvement factor wrt. InGaAs, $T_{acq} = 60$ s</td>
<td>2.3</td>
<td>2.0</td>
<td>1.7</td>
<td>2.7</td>
<td>1.9</td>
</tr>
<tr>
<td>DBX, SP1800, $T_{acq} = 60$ s</td>
<td>SNR</td>
<td>Improvement factor wrt. InGaAs, $T_{acq} = 60$ s</td>
<td>8.0</td>
<td>25.4</td>
<td>73.1</td>
<td>198.1</td>
<td>367.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>13.5</td>
<td>6.9</td>
<td>5.8</td>
<td>5.7</td>
<td>4.3</td>
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</table>
Figure 8: Emission image acquired from a 22 nm SOI chip running at $V_{dd} = 1$ V. The image was acquired using the DBX through the 20X lens and with an acquisition time of only 10 s.

better, being a factor 3 to 14 times higher depending on $V_{dd}$ (see Table 1).

PEM images from a 22 nm chip
Time-integrated images were also acquired from a 22 nm SOI chip operated at $V_{dd} = 1$ V. The PEM image in Fig. 8 was acquired through the 20X lens with the DBX camera in only 10 seconds. It can be noted how, notwithstanding the short acquisition time of only 10 seconds, a nice emission image was obtained.

Conclusions

In this work we characterized the performances of a new PEM camera prototype integrated in a Meridian-IV tool. The extended spectral sensitivity of this novel camera allows the detection of the longer wavelength portion of the chip emission spectrum that other cameras – e.g. InGaAs cameras – are not able to collect. Thus the new camera is capable of acquiring time-integrated images also at very low voltages ($V_{dd} = 0.5$ V) within 10 minutes. Through an extensive characterization at different chip operating voltages we compared the performances achievable with the new DBX camera with those of a state-of-the-art InGaAs camera. Such comparison shows that, thanks to the reduced noise of the new camera, we are able to achieve the same SNR of an InGaAs camera 5 times faster (i.e. with a 5X shorter acquisition time) when we mimic the InGaAs cutoff using the 1600 nm short-pass filter. Results are even better when we use the SP1800 that optimizes the SNR, obtaining a 14X improvement at lower $V_{dd}$.

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