Automatic Processing Scheme for Low Laser Invasiveness Electro Optical Frequency Mapping mode

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***Abstract*—Electro optical techniques are efficient backside contactless techniques usually used for design debug and defect location in modern VLSI. Unfortunately, the signal to noise ratio is quite low and depends on laser power with potential device stress due to long acquisition time or high laser power, especially in up to date technologies. Under these conditions, to maintain a good signal or image quality, specific signal or image processing techniques can be implemented. In this paper, we proposed a new spatial filtering by stationary wavelets and contrast enhancement which allows the use of low laser power and short acquisition time in image mode.**

***Index Terms*—EOP, EOFM, Stationary Wavelet Transform, Filtering, Contrast enhancement.**

I. Introduction and problem statement

VLSI failure analysis is facing endless renewed challenges induced by technology evolution. It obviously concerns fault isolation and defect location techniques. In addition to light emission techniques, methods based on laser exploit optical stimulation or optical properties of reflected beam [1]. Since its introduction, electro optical probing has become an established timing-analysis laser based technique [2], using Franz-Keldysh effect end free carrier absorption. In other words, these techniques use the observation of the emitted or reflected beam from the device under test (DUT). In the case of these optical techniques, it exists two modes: Point mode (Probing on one node) such as Electro-optical probing (EOP) or Laser Voltage Probing (LVP), or image mode Electro Optical Frequency Mapping (EOFM) also known as Laser Voltage Imaging (LVI) [3]. In our study, we will only focus on the second one. Nowadays with new VLSI technologies, 28 nm for instance, techniques using laser mode could be invasive. Consequently, it is not possible to stay several seconds on each pixel. Another problem resulting from image mode, is the noise which is the result of various phenomena especially the interaction between the light and the silicon, see Fig. 2a. To have an image with good quality in EOFM, it is possible to increase the laser's power but this solution could stress the integrated circuit (IC) or destroy it. In order to address that concern, a processing based on wavelets filtering and contrast enhancement has been suggested in this paper. The aim of this image processing scheme is to only modify the EOFM image because modification of the setup could be very complicated and expensive. This process allows experts to use a low laser to visualize the Regions of interest (ROI). Others image processing methods have already been implemented in the failure analysis (FA) community, especially for Time Resolved Imaging (TRI) [4], [5]. In the next section, EOFM background is described with an exemple of result. Then, the mathematical theory of the process is detailed. The third section is dedicated to applications. Examples with In-phase/Quadrature (IQ) images and different laser powers (10%, 20%, 40% and 100%) will be shown and compared in the discussion part. Finally, the conclusions are given with the potential perspectives.

II. Solution: filtering by SWT and contrast enhancement

A. Acquisition setup

FA techniques which take advantage of the laser properties have proved their effectiveness. Two main modes can be distinguished: point mode (EOP, LVP) and image mode (EOFM, LVI). In this study, only the image mode is taken into account. For more details about EOFM, reference [3] explains the physical principle. Applications such as EOFM, only require the identification of the core of a spot. There is no need to precisely label spot's edges, but identifying all frequencies of signals located by the spots is a key factor for the rest of the analysis. It allows the engineer to know on which node he has to probe. An example of this result is illustrated in Fig. 2a. The image is relatively noisy and some

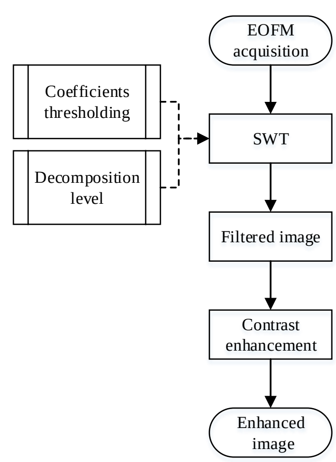
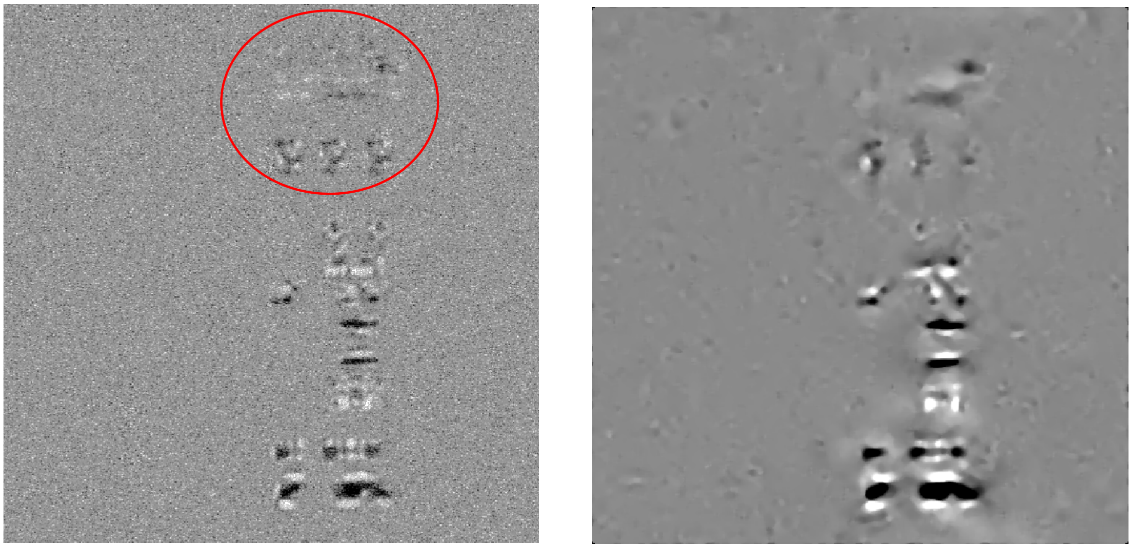


Fig. 1: Flowchart of the process.



(a)

(b)

Fig. 2: Results on EOFM IQ images with 100% without image processing (a) and 10% (b) of laser power with new post processing .

areas are not correctly visible even with 100% of laser power. Our new process allows one to obtain the kind of result shown in Fig. 2b. The flowchart' steps are illustrated below in Fig. 1 and explained in next sections.

B. Filtering by Stationary Wavelet Transform (SWT)

As mentionned previously, scanning a device in advanced technology can be invasive event even with quite low laser power or long laser exposure time. It is more invasive for recent VLSI technologies. To overcome this problem we have introduced a spatial filtering based on a combination of image processing steps. Now, each step will be detailed. The fisrt step is to remove the noise without degrading the image. Several filtering methods in image processing [6] exist, but here, a filtering process which will not introduces new pixel values is recommended in order to keep the useful information. With this purpose in mind, the filtering by stationary wavelets has been extensively studied and presented in the literature [7]. It is generally better than linear filtering such as mean, gaussian filters and non-linear filtering as median and Wiener [8]. It is recalled that in failure analysis, wavelets have already been applied to improve the signal to noise ration (SNR) in EOP [9], [10]. In the process, the first step is to decompose the image with the Stationary Wavelet Transform (SWT) at a specific level. It is similar to the Discrete Wavelet Transform (DWT) except the signal is never sub-sampled and instead the filters are up sampled at each level of decomposition. The SWT is an inherent redundant scheme, as each set of coefficients contains the same number of samples as the input. So for a decomposition of N levels, there is a redundancy of 2N (N is the signal's length). Once the image is decomposed, we obtain differents kinds of coefficients: Horizontal, vertical and diagonal [11]–[13]. Concerning the choice of the decomposition level, it will be discussed later in this paper. After that we apply a threshold to each of them in order to keep the useful coefficients. According to the literature, differents kinds of thresholding exist for wavelets coefficients [8]:

- ***Soft thresholding*** : The absolute value of all the wavelets coefficients are compared to a threshold T. If this value is greater than T the threshold is subtracted from any coefficient that is greater than the threshold. Others are set to zero.
- ***Hard thresholding*** : Hard thresholding sets any coefficient less than or equal to the threshold T to zero. Others are preserved.
- ***Universal thresholding*** : the value called *universal*, is defined by :

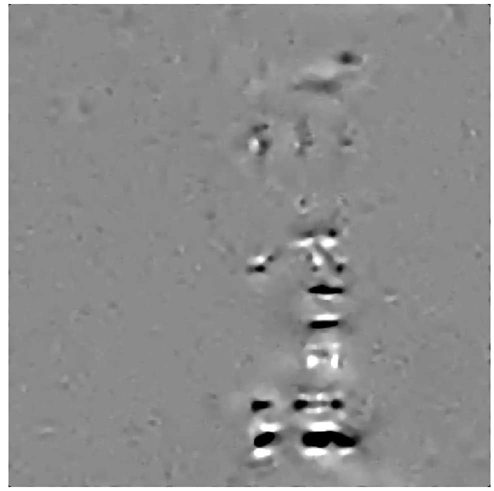
$$T_{thresh} = \sigma\sqrt{2log(N)} \tag{1}$$

where N is the length of the image and σ the noise's standard deviation. Here, T_{thresh} is used with hard thresholding. In several applications, noise is most of the time white and gaussian. This kind of white guaussian noise (WGN) is a random signal with constant power spectral density. WGN whose representation is given by (6), is independant and identically distributed (i.d.d) and drawn from a zero-mean normal distribution with variance σ^2.

$$WGN \sim N(0,\sigma^2) \tag{2}$$

According to (2), only σ^2 is unknown. That is why wavelets are useful in our study. Here, only the standard deviation could be estimated. In rare cases the noise is assumed but in others, it can be estimated by using the Median Absolute Deviation (MAD). This method has been introduced by Donoho and Johnstone in 1994 [14]. MAD is the median absolute deviation of the empirical wavelet coefficients corresponding to the first level $j1$. The reason for using these first level coefficients for the variance estimation, is that they are mostly constitued of

(a)



(b)

Fig. 3: Contrast enhancement on filtered EOFM IQ images with 10% of laser power. (a) Filtered image, (b) Enhanced image.

noise [15]. By consequences the estimated variance is given by

$$\sigma^2 = \left(\frac{MAD}{0.6745}\right)^2 \tag{3}$$

where 0.6745 is the 0.75- quantile of the standard normal distribution and

$$MAD((w_j)) = Median((|w_j|)_j) \tag{4}$$

with w_j, the wavelets coefficients. Thus, σ^2 is now known and the threshold given in (5) can be computed. Finally, the inverse transform is applied to recover the denoised image. Then, some of the ROIs could be partially or not visible. That is why we use constrast enhancement in order to make them more readable.

C. Contrast enhancement

In some applications, it is difficult to see all the characteristics of the image. That is reason why image enhancement is used to solve this problem. Contrast enhancement is one of the commonly used image processing methods [16]. In this study the contrast is enhancend by mapping the values of the input intensity image to new values according the following rule: 1% of the image is saturated at low and high intensities of the input image. An example of image improvement is illustrated in Fig. 3 with IQ images.

III. Application, results and discussion

A. Examples of application

Here the process is applied on EOFM IQ images with (10%, 20%, 40% and 100%) of the laser's power. Results are reported in Fig.(4-7). The acquisition focuses on some areas in the right corner of the image which are not visible at all with low power. The outcome of ROI identification by SWT filtering is given in Fig. 2b. For this step, SWT was used with nine decomposition levels and Daubechies wavelet. For the thresholding step, the noise is evaluated automatically by estimating its standard deviation σ. The most emissive ROI are detected but others are not perfectly viewable, see Fig. 7b red circle. The next step of the process is to highlight hidden aeras with contrast enhancement. Once the contrast is improved, the following image is obtained and illustrated in Fig. 7c. Finally, hidden ROIs are now visible with only 10% of laser power.

B. Discussion

This part addresses a discussion concercing the prior parameters for completly automate the process. More precisly this section deals with the choice of the decomposition level to justify the choice of a filtering by SWT with low laser power. Here, a qualitative approach is used by using the structural similarity index measurement (SSIM) [17] and a reference image (ground truth). This index measures the image quality in terms of luminance, contrast and structure by comparing with a reference image. It gives a score between 0 and 1.

1) Decomposition level: As presented in [9], in the wavelets theory, the maximum decomposition level (DL) is given by the following equation

$$DL_{max} = log_2 N, \tag{5}$$

with N the image' size. For example, if the used image has a size of 512×512 pixels, the DL_{max} is equal to $log_2(512) = 9$. On the one hand, DL_{max} can be computed easily. On the other hand, the expert can choose manually the DL. To show the impact of the DL, SSIM is computed as a function of the DL (from 1 to 9) for different laser powers. The results are illustrated in Fig. 8. We can notice that for high DL, the SSIM is the best for all tested laser powers. The most important aspect in this part is that results are sensibly the same for low and high laser power. Results prove the efficiency of our process in terms of image reconstitution. Engineers can have a gain between 5 and 10 about the laser power. Thus the invasive effect is considerably reduced.

(a) (b) (c)

Fig. 4: Results on EOFM IQ images with 100% of laser power. (a) Original image / (b) Image denoised with stationary wavelets transform / (c) Image with contrast enhancement.

(a) (b) (c)

Fig. 5: Results on EOFM IQ images with 40% of laser power. (a) Original image / (b) Image denoised with stationary wavelets transform / (c) Image with contrast enhancement.

(a) (b) (c)

Fig. 6: Results on EOFM IQ images with 20% of laser power. (a) Original image / (b) Image denoised with stationary wavelets transform / (c) Image with contrast enhancement.

(a) (b) (c)

Fig. 7: Results on EOFM IQ images with 10% of laser power. (a) Original image / (b) Image denoised with stationary wavelets transform / (c) Image with contrast enhancement.

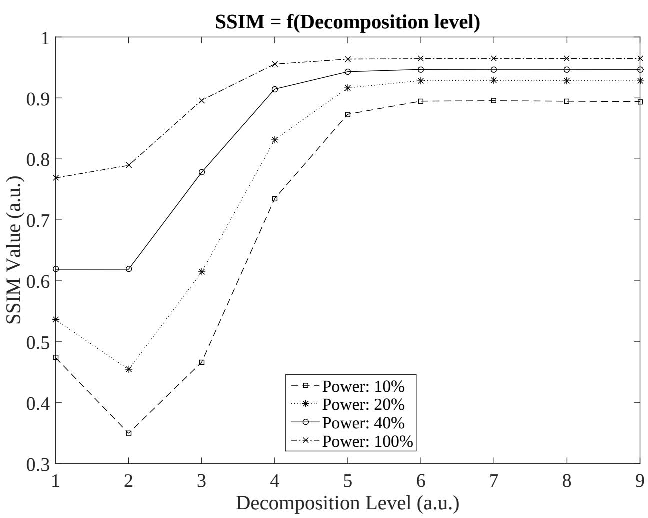


Fig. 8: SSIM index as a function of the Decomposition Level for different laser powers (10%, 20%, 40% and 100%).

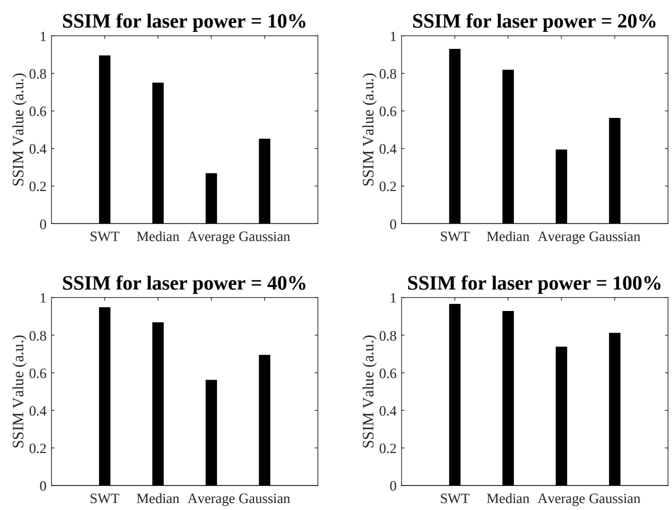


Fig. 9: SSIM index as a function of different kinds of filters (SWT, Median, Average, Gaussian) for different laser powers.

2) Choice of SWT filtering: In order to prove the efficiency of the SWT filtering, this filter is compared to others with a quantitative approach based on structural similarity index measurements SSIM. For different laser powers and different kinds of filters, the SSIM is computed. Results are given by Fig. 9. On this bar diagram, the SSIM value is always higher with SWT filtering. Also notice in the previous part, results are still the same for 100% and 10% of laser power.

IV. Conclusion and Perspectives

With new technologies like 28 nm and 15 nm, using high laser power is a real problem. But selecting low laser power provides very noisy images and engineers do not know where the ROIs appear. Filtering a noisy image is not a trivial task, especially in EOFM where detected areas are not always visible. In this paper, a filtering method combining different image processing steps has been reported. This process could be useful for the FA community because it allows to significantly reduce the invasive effect of the laser and thus saving time for the expertise. The process is fully automated and in the event of the engineer is not satisisfied with the result, he can manually adjust all the parameters. Furthermore, this study could be a complement to others existing images enhancement methods [18], [19].

In terms of perspectives, this process allows the FA community to use signal processing tools to solve their difficulties in terms of noisy acquisitions.

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