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Pattern image enhancement by extended depth of field

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ABSTRACT

Most optical defect localization techniques such as dynamic laser stimulation or photon emission microscopy require a pattern image of the device to be taken. The main purpose is for device navigation, but it also enables the analyst to identify the location of the monitored activity by superimposing it onto the pattern image. The defect localization workflow usually starts at low or medium magnification. At these scales, several factors can lead to a lack of orthogonality of the sample with the optical axis of the system. Therefore, images can be locally out of focus and poorly resolved. In this paper, a method based on Depth of Field Extension is suggested to correct the pattern image.

1. Introduction

Microscopy is one of the first tools that come to mind when objects below the millimeter scale have to be inspected, and integrated circuits are no exception to the rule. The multiplication of metal layers and the development of IC packages like flip-chip have made backside imaging mandatory for the analysis of advanced devices. In order to get through the silicon substrate, illumination wavelengths slightly above the silicon band-gap are used. As silicon partially transmits at these wavelengths, the actual pattern image is generated by light reflected by metallization layers. On older technologies, it was possible to locate some defects at die level thanks to a change of the local optical properties [1], but the progress of scaling renders that technique more difficult on sub-micrometer technologies.

When the device is analyzed with contactless optical tools like dynamic light emission [2,3] or electro-optical probing [4,5], for example, the operator relies on NIR (Near Infrared) backside imaging of the circuit to navigate on it. For various reasons, the signal acquired by the optical sensor can be of poor quality. A good focus in the microscope pattern image helps to ensure that the signal to noise ratio of the optical measurement is maximized. These features (navigation + optical measurement optimization) are even more relevant when the analysis is performed in a CAD-less framework and little knowledge of the circuit is available. So, even if NIR-microscope imaging is not directly used to get candidate localizations of defects on state of the art devices, it remains a key part of the process.

In order to maximize the energy transmitted through the silicon substrate, its thickness is reduced by different processes like polishing or milling. With the latter, an additional step of polishing is required in order to limit the scattering of light at the surface and improve image quality. Ensuring constant thickness over the whole die is difficult. Therefore, light is not focused by the microscope on the same point on every part of the device. At high magnification, it is possible to consider substrate thickness to be quite uniform because of the small field of view. This is not the case at low or medium magnification. On some devices, we have measured thickness differences of up to 60 μm. As a consequence, the image can be locally blurred. This effect can be made worse by additional parameters such as the tilt of the sample positioning table or the device's mounting on the test board, leading to an inclined die compared to the optical axis.

Some solutions exist to help to optimize pattern image quality, by allowing sample tilt to be measured and corrected, for example [6]. However, they operate at the system level, require a reference sample to do the alignment and perform better if the substrate surface is flat. In the case of high local curvature, the tilt correction cannot grant a completely sharp image.

Determining the correct focus point has been a historical concern of microscopy [7]. One of the major issues is that the object to be analyzed can have a depth that is bigger than the depth of field of the optical system. It may lead to an image in which some parts of it, the ones that are out of the depth of field, are out of focus. In order to build a completely sharp image, a method has been suggested in [8] based on defining a local focus measure

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and acquiring several images of the same scene at different focal heights. At the time, it was mainly used for 3D estimation of the scene by adding depth information.

In this paper, correcting pattern images using the Depth of Field Extension algorithm is reported. The Depth of Field Extension (DFE) and Shape From Focus (SFF) processing will be discussed in details in the next section. In the third section, some results on images acquired on a 90 nm microcontroller are presented. The forth section is dedicated to some potentially interesting applications of DFE and SFF. Finally, a conclusion is given.

2. Sharp image reconstruction methodology

2.1. General overview

The DFE and SFF algorithms require that a set of images (also named the stack, hereafter) of the same scene be acquired at different focal heights. Each image is considered as an optical slice of the scene to rebuild. For the results discussed in this paper, images have been acquired manually, but it can be automated by moving the sample table or the objective lens, and acquiring an image at each step.

The process is outlined in Fig. 1. The partially blurred image has been computed for this illustration and was not acquired on any real device. Let us consider a pixel p, located at the position (i,j) in the kth image of the stack. For every $p(i,j)$ of each image from the stack, a local focus measure is computed for a neighborhood of size $a \times a$. By the end of the process, a set of focus measures, whose length is defined by the number of images in the stack, is associated to every pixel p. The highest value in the set indicates in which image the local focus is optimum and gives the depth information. The image in which each pixel intensity indicates the depth at which best focus was achieved is called a depth map. The 3D display of the depth map gives the shape of the object, this process is known as Shape From Focus (SFF). In order to avoid aliasing effects in the depth estimation, interpolation can be performed. The 2D reconstruction of sharp images is achieved by setting the value $p(i,j)$ equal to the one in the image that produced the highest focus measure at (i,j).

2.2. Focus measure operator

Many focus operators have been reported over the years [7,9,10]. Covering all of them would go beyond the scope of this paper. In addition, not all of them are appropriate for use on pattern images. Choosing one based on the properties of these images is a more appropriate strategy. As mentioned in the introduction, the pattern image is generated by the light reflecting from metal lines. The different layers through which the light is transmitted impact the signal intensity, leading to a change of gray value in the final image. The objects constituting a circuit (transistors, metallization, etc.) are constructed with straight lines, so sharp edges can be expected in the pattern image. Because of this property, the choice of a focus measure operator based on image gradient makes sense. The variance of Tenenbaum's gradient (abbreviated hereafter as TENVAR) is one of the most efficient [10]. It is defined as [11]:

$$\phi_{x,y} = \sum_{(i,j)\in\Omega(x,y)} \left(G(i,j) - \overline{G}\right)^2, \qquad (1)$$

where $\phi_{x,y}$ is the focus measure, Ω is the set of pixel coordinates located inside the measurement window, $G(i,j) = \sqrt{G_x^2 + G_y^2}$ is the gradient magnitude at location (i,j), G_x and G_y are computed with the Sobel operator [12] in the x and y directions, and $\overline{G}$ is the average gradient magnitude within the window.

If untextured parts of the image exist, i.e. parts that contain only low spatial frequencies, the main source of local signal variation will be noise. Therefore, it is possible that the TENVAR operator can break down. For these areas, it may be more difficult to achieve perfect image reconstruction and depth estimation.

3. Application of depth of field extension

3.1. Acquisition conditions

DFE is applied to a set of images acquired on a 90 nm microcontroller with a 20× magnification and the InGaAs sensor of Hamamatsu's TriPhemos system. The stack is composed of 35 images and the pitch between each image is 2 µm, meaning that

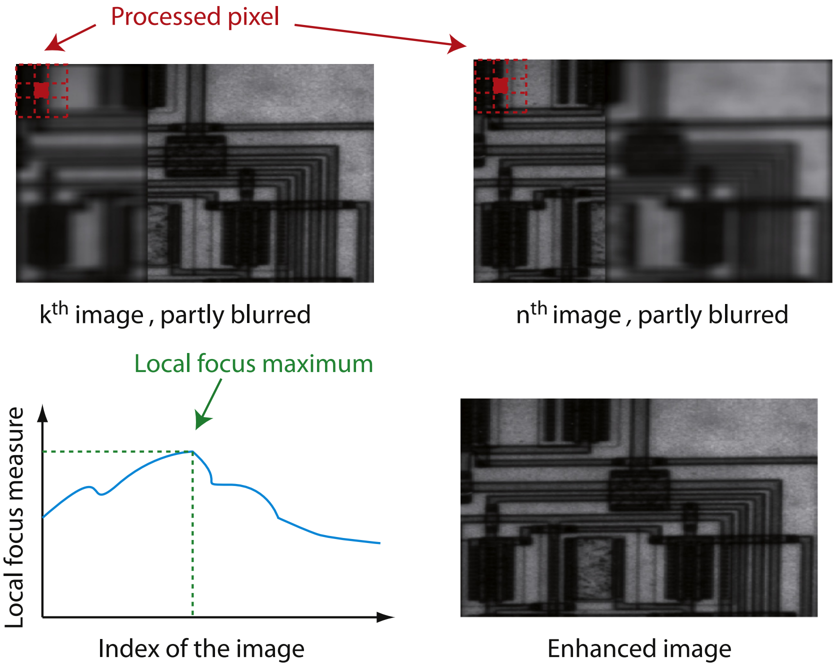

Fig. 1. Example of the DFE reconstruction.