Near-IR Spectral Imaging of Semiconductor Absorption Sites in Integrated Circuits

E. C. Samson*, C. M. Blanca, and C. Saloma
National Institute of Physics, University of the Philippines,
Diliman, Quezon City 1101
E-mail: esamson@nip.upd.edu.ph

ABSTRACT

We derive spectral maps of absorption sites in integrated circuits (ICs) by varying the wavelength of the optical probe within the near-IR range. This method has allowed us to improve the contrast of the acquired images by revealing structures that have a different optical absorption from neighboring sites. A false color composite image from those acquired at different wavelengths is generated from which the response of each semiconductor structure can be deduced. With the aid of the spectral maps, nonuniform absorption was also observed in a semiconductor structure located near an electrical overstress defect. This method may prove important in failure analysis of ICs by uncovering areas exhibiting anomalous absorption, which could improve localization of defective edifices in the semiconductor parts of the microchip.

INTRODUCTION

Optical beam-induced current (OBIC) imaging by laser scanning microscopy is becoming an important technique in analyzing defects and failures in integrated circuits (ICs). This method was further enhanced when coupled with traditional confocal reflectance microscopy (Takasu, 2001; Daria et al., 2002; Miranda & Saloma, 2003; Cemine et al., 2004). An OBIC image is a map generated from the current magnitudes that are induced in an IC when an optical probe is scanned across it. This current arises from an illuminated semiconductor material due to carriers that have absorbed photon energy from the probe. This occurs if the photon energy exceeds the band-gap energy of the semiconductor (Takasu, 2001; Beauchêne et al., 2003).

Defects in integrated circuits are identified in OBIC images as sites having unusually high or low intensity values (Takasu, 2001). Sites exhibiting high OBIC magnitudes can be due to impurities in the semiconductors. Impurities have been shown to increase the optical absorption coefficient of silicon, the customary semiconductor used in ICs (Falk, 2000), making them potential sites of anomalous optical absorption; thus the unusual magnitudes of the induced current.

Analysis of these anomalous absorption sites may become problematic due to the poor contrast and lack of axial resolution of OBIC images. In order to attain a high-quality image, high intensities of light must be utilized as a probe. This presents yet another problem since imaging will be confined to sites near the surface of the IC due to this high-intensity requirement. Thus, it is essential to develop a method that gives high-contrast OBIC images and, at the same time, capable of imaging deep inside an IC.

It has been reported that the absorption coefficient of silicon increases exponentially with wavelength in the near-infrared region (Jellison & Modine, 1982). The local change in absorption behavior can be exploited to

*Corresponding author

provide contrast to reveal differences in absorption among semiconductor sites and provide a more thorough analysis of OBIC images. Probing deep inside the IC can also be performed since long wavelengths will be utilized.

In this work, we demonstrate the possibility of generating spectral maps of different absorption sites in ICs by utilizing several wavelengths in the near-infrared region as the illuminant probe. From these spectral maps, the optical response and architecture of the IC will be determined. Improvement in contrast in OBIC images is also shown.

MATERIALS AND METHODS

The imaging method in this study utilizes a confocal microscope (Fig. 1) that consists of a tunable continuous wave Ti:Sapphire laser (3900S, Spectra-Physics, Mountain View, CA) pumped by a 5 W solid-state laser (Millenia Pro, Spectra-Physics). The beam exiting the laser is focused by a doublet lens L1 (f = 100 mm) onto a 20 mm pinhole P in order to ensure a diffraction-limited illumination. The collimator L2 (f = 150 mm) expands the beam, which is redirected by a beamsplitter BS to overfill the back aperture of L3. The objective lens L3 (NA = 0.50, Olympus, Japan) focuses the beam on the integrated circuit (IC) sample

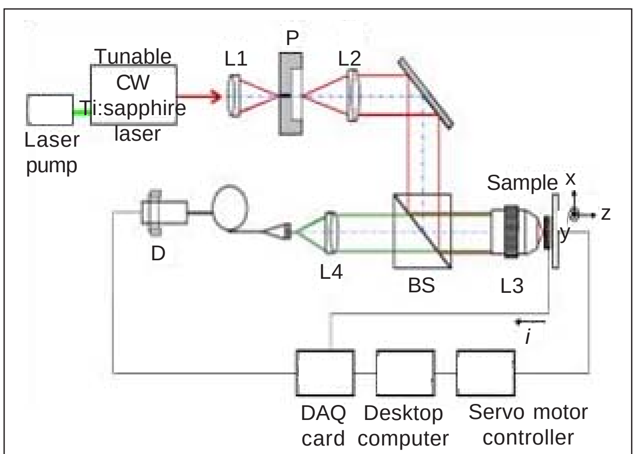

Fig. 1. The optical setup. The tunable Ti:Sapphire laser is pumped by a solid-state laser. The laser output is spatially filtered, collimated, and focused on the sample by an objective lens. The reflected signal is detected by a PMT. OBIC measurements are directly obtained by the data-acquisition card.

mounted on a scanning stage. The reflected light is collected by a tube lens L4 (f = 80 mm), focused onto a 52 mm multimode optical fiber, and then directed to a photomultiplier tube (H5784, Hamamatsu, Japan). The average power entering the microscope is approximately 40 mW.

Data acquisition and control are managed by a computer-mounted digital-to-analog converter card (National Instruments). This enables automatic control of the scanning stage (PT3-Z6, Thorlabs, New Jersey) down to a 50 nm step size in the x, y, and z directions using a custom-coded software (Labview 6i). Acquisition of detector data and OBIC measurements from the sample are controlled by the same software.

Utilizing an illumination wavelength of 750 nm, two-dimensional (x-y plane) confocal reflectance images (100×100 pixels) are acquired from the IC sample, covering an area of 200×200 mm^2. OBIC images (100×100 pixels) of the sample are acquired at the axial position giving the highest reflectance signal (z = 0). To observe the spectral response of the current generated by the sample, the illumination wavelength is varied (from 720 to 850 nm) within the tunable range of the laser.

RESULTS AND DISCUSSION

OBIC images were first obtained from a photodiode array sample. A confocal reflectance image of the specific site in the array is shown in Fig. 2(a). The OBIC images acquired at different illumination wavelengths from the system are shown in Fig. 2(b).

As can be noted from the images, certain structures in the sample do not generate any induced current when longer wavelengths (e.g., 825 nm) are used, despite these wavelengths being above the band gap of the semiconductor present in the sample [gallium arsenide (GaAs), 1240 nm] (Kittel, 1996). When shorter wavelengths illuminate the sample (e.g., 750 nm), a greater number of semiconductor structures become apparent in the OBIC images generated by the optical system. This is more evident if a line scan is taken along the 750 nm image and compared with that of the image obtained using 825 nm [refer to Fig. 2(c)]. We can

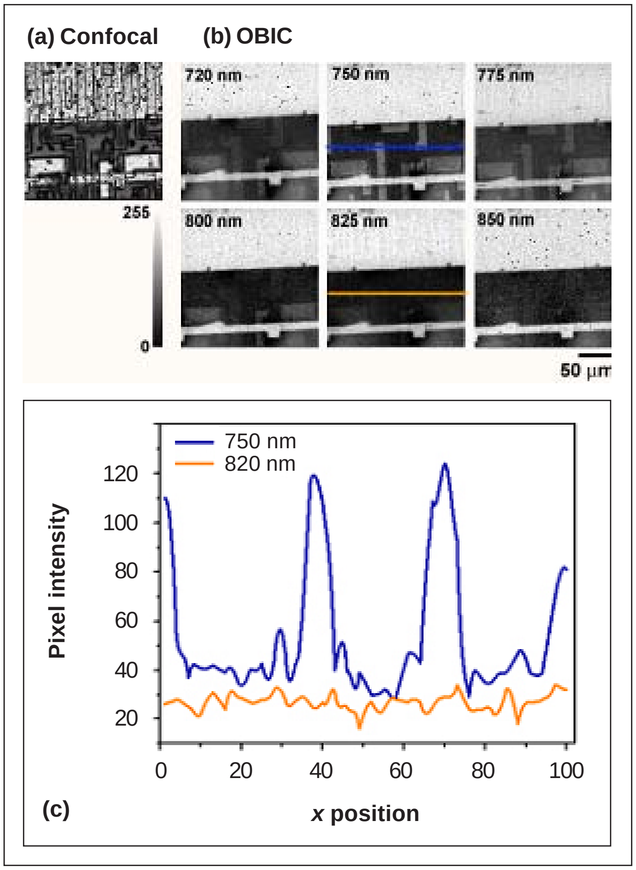

Fig. 2. (a) Confocal and (b) OBIC images of a photodiode array. The confocal image was acquired at the focus of the system using 750 nm. The OBIC images shown are taken using different illumination wavelengths (720, 750, 775, 800, 825, 850 nm). (c) Line scans of the images reveal structures that appear on certain wavelengths (750 nm) which are previously absent on others (825 nm).

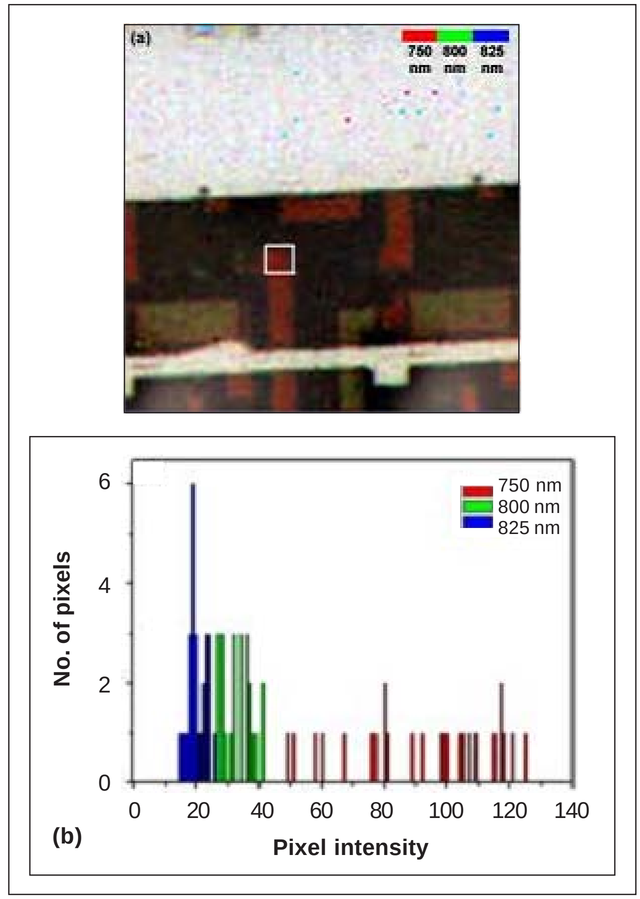

Fig. 3. (a) Composite image (area of 200x200 mm^2) of the photodiode array generated from the OBIC images taken at 750, 800, and 825 nm. The OBIC images are masked each in red (750 nm), green (800 nm), and blue (825 nm). The composite image reveals the optical response of the semiconductor with varying wavelengths as shown when (b) a histogram of a particular region [bounded area in (a)] is generated.

observe high OBIC measurements in the 750 nm image, while the longer wavelength scan contained only background signal. Clearly, higher contrast can be obtained when the illumination wavelength used to probe the IC sample is varied.

To visualize further the appearance of the IC structures for each change of wavelength, three images corresponding to different illumination wavelengths (750, 800, and 825 nm) were rendered in false color. The image taken at 750 nm was done in red, the 800 nm in green, and the 825 nm image was done in blue. The three images were superimposed and the resulting composite OBIC image is shown in Fig. 3(a). This image reveals the spatially resolved spectral absorption of the various semiconductor components.

It should be noted that the structures appearing in white in this composite image generate OBIC in all three wavelengths because all three color components are present. If structures that are more of a shade of a particular color are seen, it can be inferred that these parts appear only when the corresponding wavelength is used as illuminant. For example, the red structures would tend to absorb more at 750 nm than longer wavelengths.

A histogram of the color components of a specific structure in the composite image can be generated [Fig. 3(b)] to analyze easily on which wavelength a structure appears. Since all three color components are present in the structure, it suggests that this particular structure generates OBIC in all three wavelengths. But as indicated by its high intensity from the histogram, a greater amount of OBIC is generated when 750 nm is used as the optical probe.

The semiconductor components of the photodiode were fabricated using GaAs that has a band gap of 1240 nm, which could easily be bridged by the longest wavelength we have used (850 nm) and OBIC should have already occurred. The absorption contrast of the image could have been provided by the varying thicknesses of the semiconductor architecture. This would still have to be verified using scanning electron microscopy.

Finally, in order to observe how optical absorption is affected by the presence of defects, an IC sample having a site with electrical overstress (EOS) was placed in the system. A confocal image of the defect (encircled region) and its surrounding structures is seen in Fig. 4(a), and the OBIC images acquired using 750 and 800 nm as illuminants are shown in Figs. 4(b) and 4(c), respectively.

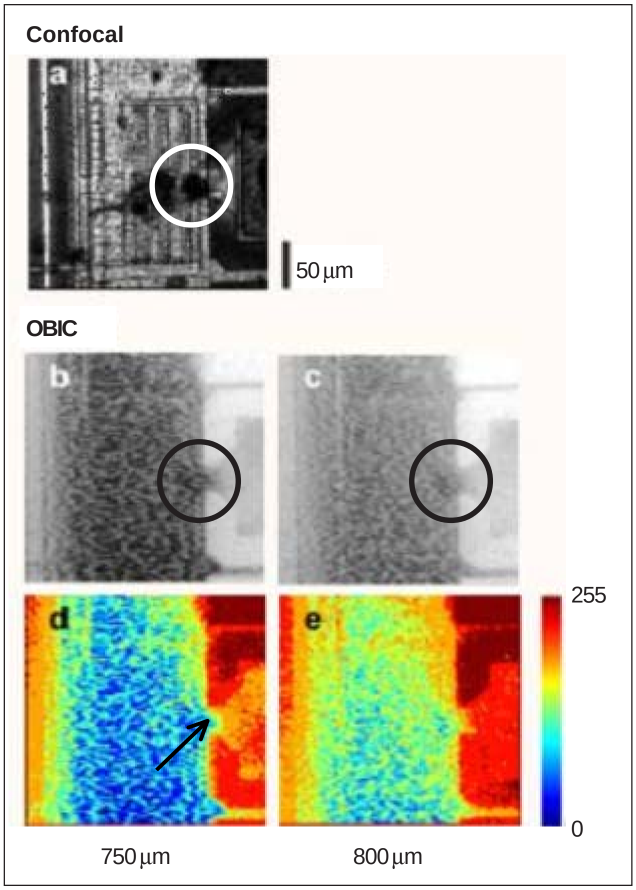

Fig. 4. (a) Confocal and (b) OBIC images of an integrated circuit with an electrical overstress defect (encircled region). The OBIC images are taken using 750 and 800 nm. (c) False color images of the OBIC reveal nonuniform generation of OBIC near the defect area. Arrow indicates a disruption of OBIC that could be due to the defect.

To perceive the difference in the generation of OBIC in the sample, the two images were rendered in false color [Figs. 4(d) and 4(e)]. It can be noticed in the 750 nm image that there is a slight disruption in OBIC generation in the area next to the defect (indicated by arrow), though it is expected that OBIC would occur continuously in this area since it is not damaged physically by EOS, as shown in the confocal image. This is also true for the image taken under 800 nm, though the disruption is to a lesser extent. Hence, the proper choice of illumination wavelength can facilitate easier localization and identification of defective sites.

Another observation from the images is the nonuniform distribution of OBIC even for a single structure. A greater concentration of OBIC is located at the upper right corner of the image as compared with the region below it even though they are of the same material and structure. A possible explanation is that the optical absorption of the material is not uniform throughout the structure, having a deviation of 33% of the maximum OBIC signal. Another thing that can be noted is when 800 nm is used, there is an increase in OBIC at the upper and center right portions of the image albeit the intensity remains the same at the lower regions. This may again be attributed to nonuniform absorption throughout the semiconductor.

Though it is still needed to be compared with a sample having the same structure without a defect, the above observations are enough to suggest that the architecture of the imaged semiconductor is not homogeneous. This inhomogeneity is peculiar since the semiconductor is of a single type and belongs to a single structure in the IC. Whether this is brought about by the defect will be determined when the comparison to a nondefective sample is performed.

CONCLUSION

We have derived composite spectral absorption maps of semiconductor sites on integrated circuits. Various components respond differently to different illumination wavelengths, enabling us to map out the topography of the absorption characteristics of the IC. It is possible to improve the analysis of semiconductor structures in an integrated circuit when the wavelength of the optical probe in OBIC imaging is made to vary. This method allows us to image structures that are not evident with longer wavelength illumination; thus, enhancing the contrast of the images obtained. Furthermore, the method revealed how electrical overstress changes the absorption properties of neighboring semiconductor regions disrupting the absorption homogeneity of the semiconductor. This disturbance can only be detected at specific wavelengths and cannot be seen if multiwavelength spectral imaging is not employed.

ACKNOWLEDGMENTS

The authors acknowledge the funding provided by the Office of the Vice Chancellor for Research and Development of the University of the Philippines, Diliman, and Bernardino Buenaobra for the acquisition software he developed.

REFERENCES

Beauchêne, T., D. Lewis, F. Beaudoin, V. Pouget, P. Perdu, P. Fouillat, & Y. Danto, 2003. A physical approach on SCOBIC investigation in VLSI. *Microelectron. Reliab.* **43**: 173–177.

Cemine, V.J., B. Buenaobra, C.M. Blanca, & C. Saloma, 2004. High-contrast microscopy of semiconductor and metal sites in integrated circuits via optical feedback detection. *Opt. Lett.* **29**: 2479-2481.

Daria, V.R., J.J. Miranda, & C. Saloma, 2002. High-contrast images of semiconductor sites via one-photon optical beam-induced current imaging and confocal reflectance microscopy. *Appl. Opt.* **41**: 4157–4161.

Falk, R.A., 2000. Near IR absorption in heavily-doped silicon: An empirical approach. *International Symposium for Testing and Failure Analysis*.

Jellison Jr., G.E. & F.A. Modine, 1982. Optical absorption of silicon between 1.6 and 4.7 eV at elevated temperatures. *Appl. Phys. Lett.* **41**: 180–182.

Kittel, C., 1996. Introduction to solid state physics, 7th ed. Wiley, New York: Chap. 8.

Miranda, J.J. & C. Saloma, 2003. Four-dimensional microscopy of defects in integrated circuits. *Appl. Opt.* **42**: 6520–6524.

Takasu, S., 2001. Application of OBIC/OBIRCH/OBHIC: Semiconductor failure analysis. *JEOL News.* 36E: 60–63.