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From EBIC Images to Qualitative Minority Carrier Diffusion Length Maps

O. Marcelot and P. Magnan

Abstract—A novel method is presented with the aim to perform minority carrier diffusion length map on cross-sectional samples. The method is based on one Electron-Beam Induced Current (EBIC) acquisition and on the analyze of the EBIC signal slope variation on each scanned points. This method is applied on a pinned photodiode array realized on a low doped silicon epitaxy, and the electron diffusion length map which is extracted is in good accordance with our expectation taking into account the doping distribution of the device. A TCAD simulation also confirms quantitatively the measured diffusion length map. Advantages and drawbacks of this method are discussed in this study.

Index Terms—Electron-beam-induced current (EBIC), scanning electron microscopy (SEM), semiconductor material measurements, CMOS Image Sensors, Simulation, Deep Submicron Process, CMOS, solid-state image sensor.

I. INTRODUCTION

ELECTRON Beam Induced Current (EBIC) is a common Scanning Electron Microscopy (SEM) technique used with the aim to extract physical parameters like the minority carrier diffusion length [1], [2], [3], [4], [5], or the minority carrier lifetime [6], [7], [8], [9]. The minority carrier diffusion length is generally extracted from a simple structure including a PN junction. Knowing such parameters is crucial because there are key physical parameters in the design of photodiodes included in CMOS Image Sensors (CIS). Indeed, generated electrons in the silicon substrate by the incoming photons have to be collected by the photodiode before their recombination with holes, which depends on the doping concentration, and eventually on the presence of defects. The electron recombination is mainly driven by the electron lifetime and by the electron diffusion length in the silicon, the last being the important parameter studied in this paper. Nowadays, CIS developed for consumers or scientific applications may use photodiodes with particular doping distribution and low-doped epitaxies on more doped silicon substrates [10], [11], [12], [13]. Imaging in two dimensions the minority carrier diffusion length in such device would be very useful for the pixel designer and for the simulator calibration.

Authors has worked on the minority carrier lifetime map using the transient EBIC method [9]. This technique requires to blank the SEM beam at each scanned point, and to deal with a very fast and very low and noisy EBIC current which is tricky to analyze [14]. Tabib-Azar et al proposed a diffusion length mapping method based on the acquisition of several plan view EBIC images for various beam energies [15]. In this method, the diffusion length on each point is extracted by computing the EBIC current measured for the various beam energy. The drawbacks of this method is the use of high beam energies which strongly increases the electron hole pair generation volume and decreases the spatial resolution, and the doping layers which have to be uniform all along the sample depth. Other methods based on electroluminescence [16] or microwaves [17] were developed; however, to our knowledge, no minority carrier diffusion length mapping methods has been developed by using one single EBIC image acquisition.

The purpose of this work is therefore to propose an original method that permits to extract the minority diffusion length map from an unique EBIC picture, with the possibility to study non-uniformly doped sample. After describing the EBIC treatment method, experimental details are detailed and the first results presented. Then, Technology Computer Aided Design (TCAD) simulations are employed for validation of experimental results.

II. EBIC DATA PROCESSING

EBIC measurement consists in imaging the current created by the electron beam and collected by a PN junction or a Schottky diode. Electron-hole pairs are created in a volume beneath the beam impact, and minority carriers can reach the electrical junction by diffusion if they are not recombined before, giving rise to a current. The EBIC current is maximum at the position of the junction. Two experimental configurations are generally observed (Fig. 1):

- plan view configuration: the electron beam is scanned over the surface of the electrical junction
- cross-section view configuration: the sample is cut and the electron beam is scanned along the junction depth

For our devices made with a CMOS imaging process, dielectric silicon oxides are deposited on top of the silicon surface.
To do so, the formalism of [21] is used and the beam current is monitored using a Faraday cup on a deep submicrometer CMOS imaging process. The above expression gives a correct estimation of the minority carrier diffusion length for one or two different P doped layers, but gives a rough quantitative estimation for more than three P doped layers, because the slope variation is only valid for the first P doped layer over the substrate.

In order to extract a minority carrier diffusion length map from the 2D EBIC picture, a matrix including the distances from each pixel to the N+ junction is created, and the formalism described above is applied. In addition, the following parameters have to be entered:

- parameters of the straight line \((A, L_{d,\text{sub}})\)
- position of the N+ junction
- position for which the slope is changing (for the calculation of \(d'\))

They can be easily extracted from a simple 1D profile analysis.

III. EXPERIMENTAL

EBIC acquisitions are performed on a tungsten filament FEI Inspect S-50 SEM, and the beam accelerating voltage is set to 10 keV in order to keep good spatial resolution. Indeed, at 30 keV the generation volume of electron-hole pairs simulated with Casino [20] has a diameter of about 6 \(\mu m\), while at 10 keV it is less than 1 \(\mu m\). The depth of the generation volume is estimated at 0.56 \(\mu m\). Moreover, the beam current is kept at a reasonable value with the aim to avoid a high injection regime. To do so, the formalism of [21] is used and the beam current limit is set to 40 pA, which corresponds to an injection 10x lower than the high injection limit regime in the lowest doped layer. The beam current is monitored using a Faraday cap mounted on stage.

A. Sample description

Measurements are performed on a sample including an array of pinned photodiodes [22] with a pitch of 4.5\(\mu m\), manufactured on a deep submicrometer CMOS imaging process. The

![Fig. 2. Schematic view of two EBIC signal extractions; (a) uniformly p doped substrate, and (b) a low doped p type layer is put on the p doped substrate.](image)

- if the p substrate is uniformly doped, for \(d > d_1\) the curve follows the straight line \(y = A - d / L_{d,\text{sub}}\)
- if the substrate is composed of one low doped p layer (from \(d_1\) to \(d_2\)) over a more doped p layer (for \(d > d_2\)), the curve shows a smaller slope between \(d_1\) and \(d_2\) because the minority diffusion length is longer. Thus, the curve follows the straight line \(y = A - d / L_{d,\text{sub}}\), only for \(d > d_2\).

If \(\Delta\) is the difference between the curve and the straight line, so \(\Delta/d'\) is an estimation of the slope variation compared to the straight line, \(d'\) being the distance counted negatively from the point where \(\Delta\) starts to be non-zero (illustrated in the Fig. 2).

\[
\Delta = Ln \left( I_{EBIC} \times d^{-n} \right) - (A - d / L_{d,\text{sub}}) \tag{2}
\]

Finally, the minority carrier diffusion length along the distance \(d\) can be estimated by weighting the substrate diffusion length \(L_{d,\text{sub}}\) with the slope variation \(\Delta/d'\).

\[
L_{\text{diff}} (d) = \frac{1}{1/L_{d,\text{sub}} + \Delta/d'} \tag{3}
\]
Fig. 3. (a) Schematic cross-sectional view of the photodiode array. Red colors means N doping, blue colors represents the P doping and the low doped P epitaxy is white. PW is for Pwell, SN is for Sense Node, PPD is for pinned photodiode, and TG is for Transfer Gate. (b) Plan view of the photodiode array with an example of cut plane used for the cross-section preparation.

Fig. 4. (a) EBIC image of the sample measured with the Keithley current preamplifier. Five pinned photodiodes are visible in this view. A 1D profile cut is also shown with the current in logarithmic scale. (b) minority diffusion length map deduced from the EBIC image.

Fig. 5. (a) EBIC image of the sample measured with the Keithley Electrometer. Three whole pinned photodiodes are visible in this view. A 1D profile cut is also shown on the right with the current in logarithmic scale. (b) minority diffusion length map deduced from the EBIC image, in µm.

The EBIC current in logarithmic scale and is shows a noisy EBIC signal because of a low beam energy and current. Therefore, the minority carrier diffusion length map is very noisy under the epitaxy level. However, the map indicates two areas outside the photodiodes where the diffusion length is different; in the epitaxy region the diffusion length is estimated at around 40 µm, and in the substrate it is estimated at around 10 µm. Considering the design given in Fig. 3, this observation is consistent with what it could be expected.

With the intention of improving the signal to noise ratio, the EBIC image is formed in the following with a more sensitive equipment, the Keithley 6514 Electrometer.

C. EBIC Acquisition using an electrometer

A special Lab View program is made and drives a Keithley 6514 Electrometer connected to the sample, a function waveform generator Agilent 33220A, and a DC power supply Agilent E3640A. The goal of the two last equipments is to control the SEM scan in horizontal axis and in vertical axis respectively. Due to the long integration time needed by the Electrometer at each pixel, an image of 344 x 122 pixels requests about 30 min.

The Fig. 5 is showing an EBIC image obtained at a x5000 magnification with the extracted minority carrier diffusion length map. A 1D EBIC current profile extracted from the EBIC image demonstrates a much better signal to noise ratio. Therefore, the minority carrier diffusion length map is much less noisy, and is still in good agreement with what it could be expected from the studied structure. In the epitaxy region the diffusion length is estimated at around 20 µm, and in the substrate it is estimated at around 5 µm.

A last measurement is performed on the edge of the photodiode array (Fig. 6), in order to verify the diffusion length extraction on an unsymmetrical structure. The matrix of distances used for the extraction of the diffusion length is modified in a way that it takes into account the end of the photodiode array on a part of the image. In spite of a strong EBIC signal only localized in the lower part of the studied region, the minority diffusion length map given by the Fig. 6 shows constant values in the substrate and higher but homogenous values in the epitaxy. In addition, the minority diffusion lengths in the continuation of the photodiode remains lower compared to the epitaxy, because of the presence of...
Cut Y (µm)
maps obtained by EBIC measurement.

In the next part, TCAD simulations are run
information given by other P doping layers can be used only
are just reliable for the two first P doping layers, and the
doping structures. However, the absolute extracted values
image acquisition, and on unsymmetrical and inhomogeneous
map minority carrier diffusion lengths, from only one EBIC
therefore perfectly compatible with the desired outcome.

Pwell doping. The minority carrier diffusion length map is
therefore perfectly compatible with the desired outcome.

All these observations confirm that this technique is able to
map minority carrier diffusion lengths, from only one EBIC
image acquisition, and on unsymmetrical and inhomogeneous
doping structures. However, the absolute extracted values
are just reliable for the two first P doping layers, and the
information given by other P doping layers can be used only
for comparison. In the next part, TCAD simulations are run
on the tested device in order to confirm the diffusion length
maps obtained by EBIC measurement.

IV. TCAD SIMULATION AND DISCUSSION

The device is simulated in two dimensions using the TCAD
Synopsys Sentaurus SDE tool, and the doping distribution
is generated from Secondary Ion Mass Spectroscopy (SIMS)
profiles and from the layout description of the device given in
Fig. 3. A short electrical simulation is run with the Sdevice
tool for a bias equal to 0 V for all contacts, and the two
dimensional electron lifetime and mobility are extracted. The
electron diffusion length is then computed using the following
expression:

\[ L_{\text{diff},e} = \sqrt{\frac{\lambda_e \mu_e kT}{q}} \]  

where \( \lambda_e \) is the electron lifetime, and \( \mu_e \) the electron mobility.

As it can be seen, the quantitative distribution of electron
diffusion length looks identical to the measured one: the
longest diffusion length is located in the epitaxy
(\( L_{\text{diff},e} = 175 \mu\text{m} \)), and the smallest one in the substrate
(\( L_{\text{diff},e} = 9 \mu\text{m} \)). The Pwell region has a small diffusion
length (\( L_{\text{diff},e} = 20 \mu\text{m} \)), which is compatible with the
observation made in the Fig. 6. Absolute TCAD values are
different compared to the measured one, because:

- the measured minority carrier diffusion length is probably
  underestimated, because of the sample preparation which
  alters the surface and increases the carrier recombination
  rate.
- the TCAD simulator uses one specific model for the
  lifetime estimation [23], and other models may give
different results.
- the TCAD simulation does not take into account the
  pollution or the presence of defects in the silicon, which
  can affect the electron diffusion length.

In a general way, limitations can be found in our method.
Firstly, although the P substrate may be considered as semi-
infinite, the P low doped silicon layer is thin compared to the
measured diffusion length, which leads to an underestimation
of the minority diffusion length in the epitaxy as explained
in [24]. Thus, the minority diffusion length map has to be
observed carefully in the case of a layer has a diffusion length
similar or higher than the layer thickness, because values are
probably underestimates. Second, the width of the N doped
layers in our sample (orthogonal direction in Fig. 3 (a)) is
about 1 µm, which is only twice the depth of the generation
volume. In this case, the error in extracting the diffusion
lengths does not exceed 4 % [5], which is reasonable. Finally,
as written before, the surface quality of the sample impacts the
surface carrier recombination rate which results in a possible
underestimation of the diffusion length.

V. CONCLUSION

A novel method has been developed in order to extract a mi-
nority carrier diffusion length map on semiconductor devices,
from an unique EBIC picture. To do so, an EBIC acquisition is
performed on the device under test prepared in cross-section,
and the EBIC signal slope variation is computed on each
point, which allows to deduct the minority carrier diffusion
length. In order to obtain a good spatial resolution (lower
than 1µm), the beam energy is decreased as much as possible
(10keV), and the beam current is kept low with the aim to
perform the experiment in low injection regime. The results
are in a good agreement with what is expected according to

Fig. 6. (a) EBIC image of the sample measured with the Keithley Electrometer, on the photodiode array edge. Only one pinned photodiode is visible in this view. A 1D profile cut is shown on the right with the current in logarithmic scale. (b) minority diffusion length map deduced from the EBIC image, in µm.

Fig. 7. (a) TCAD simulation of the doping distribution centered on one pinned photodiode. (b) TCAD simulation of the electron diffusion length.
the sample design, and the TCAD simulation looks similar to the measurement, although the absolute diffusion lengths are different.

The drawbacks of this technique are the weak EBIC signal which requires to use very sensitive ammeter, and the fact that the minority carrier diffusion length can be extracted in an absolute way only on the first two P layers. Then, the measurement of thin epitaxy or doping layers can generate an underestimation of the diffusion length because its extraction is performed outside recommended conditions.

This technique, easy to set up, allows to quickly get the electron diffusion length in epitaxy for instance, or to qualitatively monitor the diffusion length in more complex doping area.

REFERENCES


