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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

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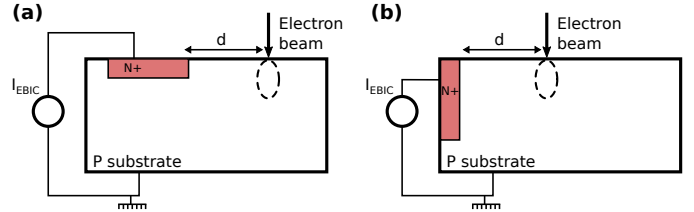


Fig. 1. Schematic view of the two main EBIC experimental configurations, (a) the plan view, and (b) the cross-section view. d is the distance between the junction and the electron beam.

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

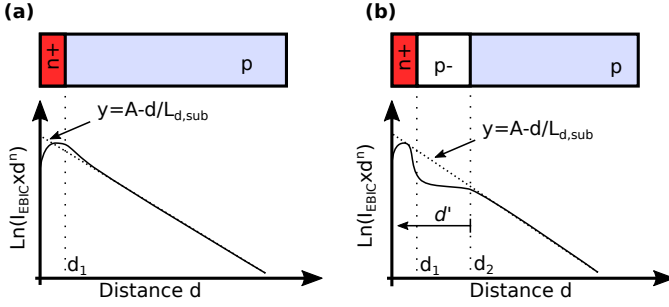


Fig. 2. Schematic view of two EBIC signal extractions; (a) uniformly p doped substrate, and (b) a low doped p type layer is put on the p doped substrate. The straight line $y = A - d/L_{d,sub}$ used for the minority carrier diffusion length extraction in the substrate is plotted in dashed line. d' is the distance counted negatively from which the curve separates from the straight line.

in a range of several micro-meters. The electron beam has to go through this dielectric, and getting a low noise EBIC signal requires to use high beam energy and current, which is not suitable. Furthermore, this configuration does not allow the analysis of different doping layers in depth. Therefore, in the following, only the cross-section configuration is used.

The analysis for the EBIC current dependence with the distance d from the junction allows the extraction of the minority diffusion length. This behavior has been intensively studied [2], [3], [18], [19], and it is established that the EBIC current follows the following law, given by:

$$I_{EBIC} = A \times d^{-n} \exp\left(-\frac{-d}{L_{diff}}\right) \quad (1)$$

where A is a constant, L_{diff} is the carrier minority diffusion length, and n is a factor depending on the surface recombination rate (parameter called s , in cm.s^{-1}) and on the sample configuration (Fig. 1). In the cross-sectional geometry, n varies between 0 ($s = 0$) and 0.5 ($s = \infty$), while in plan view, n has a range between 0.5 ($s = 0$) and 1.5 ($s = \infty$) [5]. This EBIC current approximation is accepted to be valid if the beam is kept at least two minority diffusion lengths away from the sample end, and if the excess minority carrier density is much lower than the equilibrium majority carrier density [3]. This second condition can be controlled by lowering the beam current. A third restriction comes from the mathematical simplification, and the distance d should be kept greater than the minority carrier diffusion length. In practical, this restriction is found to be severe, since straight lines can be obtained for small d [3].

From an EBIC profile, the minority carrier diffusion length can be extracted by plotting $\text{Ln}(I_{EBIC} \times d^{-n})$ versus d , the slope being equal to $-1/L_{diff}$. The parameter n being unknown, it should be adjusted in order to obtain a straight line. Actually, it gives a straight line for any value of n within the considered range. Therefore, the n variation can be used as an indicator of the error made.

In our approach, an EBIC image of a N+/P junction is acquired and the classical method described above is used to extract the minority carrier diffusion length of the substrate. To do so, $\text{Ln}(I_{EBIC} \times d^{-n})$ is plotted, and two situations are described as an example (See Fig. 2):

- if the p substrate is uniformly doped, for $d > d_1$ the curve follows the straight line $y = A - d/L_{d,sub}$, where $L_{d,sub}$ is the minority diffusion length in the substrate
- 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 $y = A - d/L_{d,sub}$ only for $d > d_2$.

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

$$\Delta = \text{Ln}(I_{EBIC} \times d^{-n}) - (A - d/L_{d,sub}) \quad (2)$$

Finally, the minority carrier diffusion length along the distance d can be estimated by weighting the substrate diffusion length $L_{d,sub}$ with the slope variation Δ/d' .

$$L_{diff}(d) = \frac{1}{1/L_{d,sub} + \Delta/d'} \quad (3)$$

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 , $L_{d,sub}$)
- 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 μm , while at 10 keV it is less than 1 μm . The depth of the generation volume is estimated at 0.56 μm . 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 μm , manufactured on a deep submicrometer CMOS imaging process. The

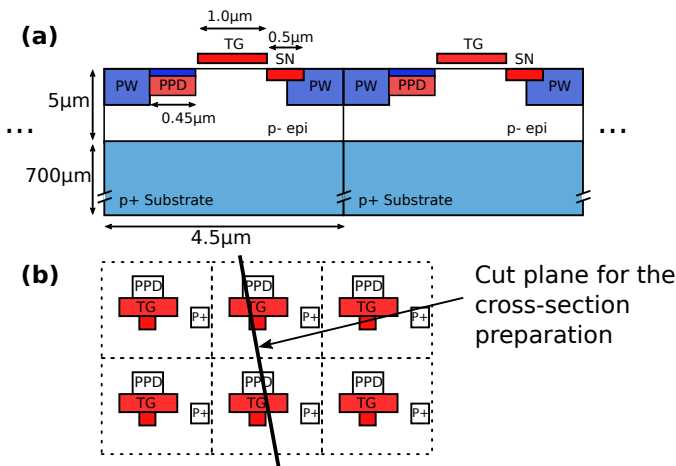


Fig. 3. (a) Schematic cross-sectional view of the photodiode array. Red colors means N doping, blue colors represents the P doping and the low doped P epitaxy is white. PW is for Pwell, SN is for Sense Node, PPD is for pinned photodiode, and TG is for Transfer Gate. (b) Plan view of the photodiode array with an example of cut plane used for the cross-section preparation.

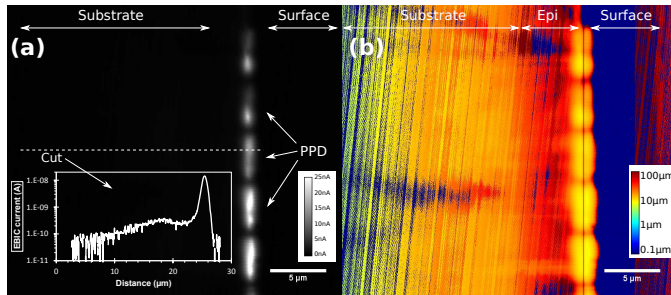


Fig. 4. (a) EBIC image of the sample measured with the SRS current preamplifier. Five pinned photodiodes are visible in this view. A 1D profile cut is also shown with the current in logarithmic scale. (b) minority diffusion length map deduced from the EBIC image.

substrate is a P doped silicon wafer with a P low doped silicon epitaxy on top, and the process uses four metal layers and thick dielectric layers which excludes EBIC observation in plan view, as said previously. The photodiodes array is cut off and polished with SiC sandpaper and an alumina colloidal solution (0.1 m), and finally bonded on a package which is mounted on the SEM holder. The Fig. 3(a) is showing a schematic cross-section of the sample. The sense node (cathode) and the Pwell (anode) are connected via a coaxial cable to external equipments for the EBIC measurement. A plan view of the photodiode array is also shown in Fig. 3(b) together with an example of cut line used for the cross-section preparation.

B. EBIC Acquisition using a trans-impedance amplifier

A SRS 570 current preamplifier is connected to the SEM video input to visualize the EBIC signal. The EBIC picture is shown by the Fig. 4, and it clearly shows five pinned photodiodes, whose EBIC signal looks different because the photodiode array is cut diagonally (Fig. 3(b)). The grey scale is converted to Ampere, by means of a 1D profile calibration with a Keithley 6514 Electrometer controlled by a Lab View program. The 1D profile in the figure gives the EBIC current in

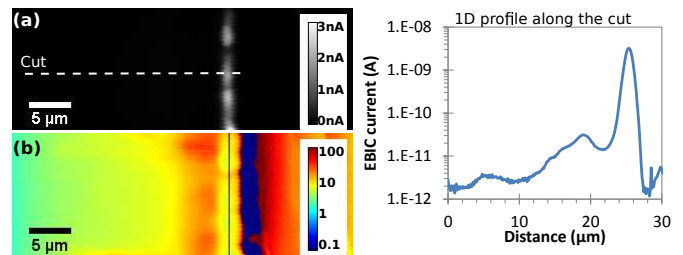


Fig. 5. (a) EBIC image of the sample measured with the Keithley Electrometer. Three whole pinned photodiodes are visible in this view. A 1D profile cut is also shown on the right with the current in logarithmic scale. (b) minority diffusion length map deduced from the EBIC image, in μm .

logarithmic scale and it 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 $40 \mu\text{m}$, and in the substrate it is estimated at around $10 \mu\text{m}$. 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 344×122 pixels requests about 30 min.

The Fig. 5 is showing an EBIC image obtained at a $\times 5000$ 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 $20 \mu\text{m}$, and in the substrate it is estimated at around $5 \mu\text{m}$.

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

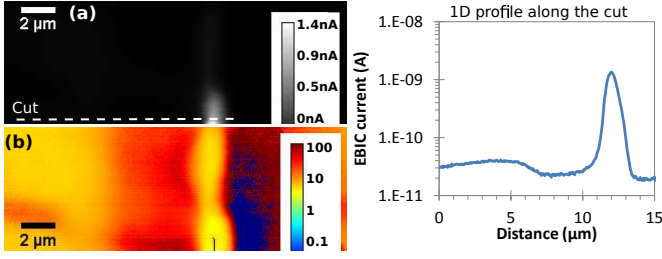


Fig. 6. (a) EBIC image of the sample measured with the Keithley Electrometer, on the photodiode array edge. Only one pinned photodiode is visible in this view. A 1D profile cut is shown on the right with the current in logarithmic scale. (b) minority diffusion length map deduced from the EBIC image,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

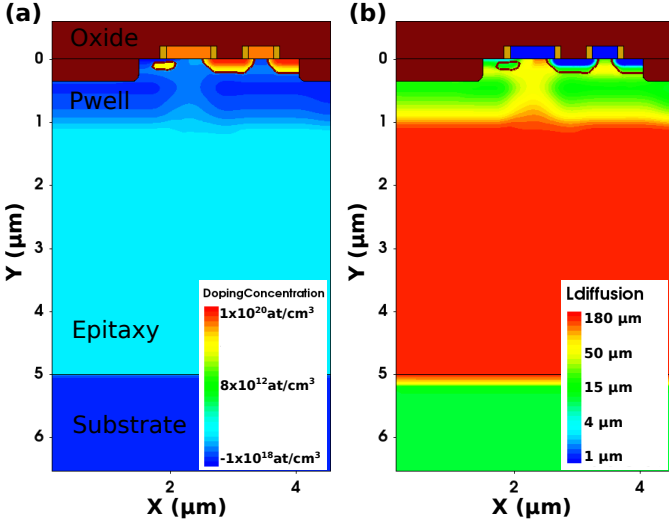


Fig. 7. (a) TCAD simulation of the doping distribution centered on one pinned photodiode. (b) TCAD simulation of the electron diffusion length.

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:

$$L_{\text{diff},e} = \sqrt{\lambda_e \mu_e \frac{kT}{q}} \quad (4)$$

where λ_e is the electron lifetime, and μ_e the electron mobility. Thus, the TCAD is not used to reproduce the EBIC experiment as it is the case in, but is only employed to simulate physical parameters at the equilibrium. The simulated doping distribution and the electron diffusion length are displayed in the Fig. 7.

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 $1 \mu\text{m}$, 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 minority carrier diffusion length map on semiconductor devices, from a 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 deduce the minority carrier diffusion length. In order to obtain a good spatial resolution (lower than $1 \mu\text{m}$), 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

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

- [1] W. H. Hackett, R. H. Saul, R. W. Dixon, and G. W. Kammlott, "Scanning electron microscope characterization of gap redemitting diodes," *Journal of Applied Physics*, vol. 43, no. 6, pp. 2857–2868, 1972.
- [2] C. Donolato, "On the analysis of diffusion length measurements by sem," *Solid-State Electronics*, vol. 25, no. 11, pp. 1077 – 1081, 1982.
- [3] D. Ioannou and C. A. Dimitriadis, "A sem-ebic minority-carrier diffusion-length measurement technique," vol. 29, pp. 445 – 450, 04 1982.
- [4] D. K. Schroder, *Semiconductor Material and Device Characterization*. Wiley-Interscience, 2006.
- [5] O. Kurniawan and V. K. S. Ong, "Generalized ebic method for extracting diffusion lengths from non-conventional collector structure," in *2006 Conference on Optoelectronic and Microelectronic Materials and Devices*, Dec 2006, pp. 113–116.
- [6] F. Berz and H. Kuiken, "Theory of life time measurements with the scanning electron microscope: Steady state," *Solid-State Electronics*, vol. 19, no. 6, pp. 437 – 445, 1976. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/0038110176900034>
- [7] M. Watanabe, G. Actor, and H. C. Gatos, "Determination of minority-carrier lifetime and surface recombination velocity with high spacial resolution," *IEEE Transactions on Electron Devices*, vol. 24, no. 9, pp. 1172–1177, Sep 1977.
- [8] D. E. Ioannou, "A sem-ebic minority-carrier lifetime-measurement technique," *Journal of Physics D: Applied Physics*, vol. 13, no. 4, p. 611, 1980. [Online]. Available: <http://stacks.iop.org/0022-3727/13/i=4/a=014>
- [9] T. Kushida, S. Tanaka, C. Morita, T. Tanji, and Y. Ohshita, "Mapping of minority carrier lifetime distributions in multicrystalline silicon using transient electron-beam-induced current," *Journal of Electron Microscopy*, vol. 61, no. 5, pp. 293–298, 2012. [Online]. Available: <http://dx.doi.org/10.1093/jmicro/dfs050>
- [10] W. Snoeys, J. D. Plummer, S. Parker, and C. Kenney, "Pin detector arrays and integrated readout circuitry on high-resistivity float-zone silicon," *IEEE Transactions on Electron Devices*, vol. 41, no. 6, pp. 903–912, Jun 1994.
- [11] P. P. K. Lee, R. C. Gee, R. M. Guidash, T. h. Lee, and E. R. Fossum, "Active pixel sensor fabricated using cmos/ccd process technology," in *In Proceedings of IEEE Workshop CCD and Advanced Image Sensors, Dana Point*, 1995.
- [12] A. J. Theuwissen, "Cmos image sensors: State-of-the-art," *Solid-State Electronics*, vol. 52, no. 9, pp. 1401 – 1406, 2008, papers Selected from the 37th European Solid-State Device Research Conference - ESSDERC07. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0038110108001317>
- [13] K. D. Stefanov, A. S. Clarke, and A. D. Holland, "Fully depleted pinned photodiode cmos image sensor with reverse substrate bias," *IEEE Electron Device Letters*, vol. 38, no. 1, pp. 64–66, Jan 2017.
- [14] O. Marcelot, S. I. Maximenko, and P. Magnan, "Plan view and cross-sectional view ebic measurements: Effect of e-beam injection conditions on extracted minority carrier transport properties," *IEEE Transactions on Electron Devices*, vol. 61, no. 7, pp. 2437–2442, July 2014.
- [15] M. Tabib-Azar, S. M. Hubbard, C. M. Schnabel, and S. Bailey, "Mapping of crystal defects and the minority carrier diffusion length in 6hsic using a novel electron beam induced current technique," *Journal of Applied Physics*, vol. 84, no. 7, pp. 3986–3992, 1998. [Online]. Available: <https://doi.org/10.1063/1.368578>
- [16] T. Fuyuki, H. Kondo, Y. Kaji, T. Yamazaki, Y. Takahashi, and Y. Uraoka, "One shot mapping of minority carrier diffusion length in polycrystalline silicon solar cells using electroluminescence," in *Conference Record of the Thirty-first IEEE Photovoltaic Specialists Conference, 2005.*, Jan 2005, pp. 1343–1345.
- [17] O. Palais, J. Gervais, E. Yakimov, and S. Martinuzzi, "Contactless mapping of lifetime and diffusion length scan map of minority carriers in silicon wafers," *The European Physical Journal - Applied Physics*, vol. 10, no. 2, p. 157162, 2000.
- [18] D. S. H. Chan, V. K. S. Ong, and J. C. H. Phang, "A direct method for the extraction of diffusion length and surface recombination velocity from an ebic line scan: planar junction configuration," *IEEE Transactions on Electron Devices*, vol. 42, no. 5, pp. 963–968, May 1995.
- [19] J. Bonard and J. Ganire, "Quantitative analysis of electronbeaminduced current profiles across pn junctions in gaas/al0.4ga0.6as heterostructures," *Journal of Applied Physics*, vol. 79, no. 9, pp. 6987–6994, 1996. [Online]. Available: <https://doi.org/10.1063/1.361464>
- [20] D. Drouin, A. Ral Couture, D. Joly, X. Tastet, V. Aimez, and R. Gauvin, "Casino v2.42a fast and easytouse modeling tool for scanning electron microscopy and microanalysis users," vol. 29, pp. 92–101, 05 2007.
- [21] H. Alexander, "What information on extended defects do we obtain from beam-injection methods?" *Materials Science and Engineering: B*, vol. 24, no. 1, pp. 1 – 7, 1994. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/0921510794902887>
- [22] E. R. Fossum and D. B. Hondongwa, "A review of the pinned photodiode for ccd and cmos image sensors," *IEEE Journal of the Electron Devices Society*, vol. 2, no. 3, pp. 33–43, May 2014.
- [23] D. J. Roulston, N. D. Arora, and S. G. Chamberlain, "Modeling and measurement of minority-carrier lifetime versus doping in diffused layers of n/+p silicon diodes," *IEEE Transactions on Electron Devices*, vol. 29, pp. 284–291, Feb. 1982.
- [24] K. L. Luke, "Determination of diffusion length in samples of diffusion-length size or smaller and with arbitrary top and back surface recombination velocities," *Journal of Applied Physics*, vol. 90, no. 7, pp. 3413–3418, 2001. [Online]. Available: <https://doi.org/10.1063/1.1400093>