NON-DESTRUCTIVE P-N JUNCTION TESTING ON THIN FILM SOLAR CELLS

D. Lausch[*,1], M. Werner[1], O. Breitenstein[2], S. Swatek[1], J. Schneider[3] and C. Hagendorf[1]
[1]Fraunhofer Center for Silicon Photovoltaics CSP, 06120 Halle (Saale), Germany
[2]Max Planck Institute of Microstructure Physics, Weinberg 2, 06120 Halle, Germany
[3]CSG Solar AG, Sonnenallee 1-5, 06766 Bitterfeld-Wolfen OT Thalheim, Germany

* Corresponding author: dominik.lausch@csp.fraunhofer.de, Phone: +49 (0) 345 5589-447, Fax: +49 (0) 345 5589-101

ABSTRACT: Non-destructive and quantitative measurements of the electron beam induced current (EBIC) as a function of the electron beam energy were performed on thin film solar cells from different technologies in order to determine the depth and width of the p-n junction by using an iterative deconvolution algorithm. Additionally, the exact position of the p-n junctions of the thin film solar cell is confirmed independently by EBIC investigations at cross sections. We show that voltage dependent EBIC investigations on the native surface and EBIC measurements at cross sections are in good agreement.

1 INTRODUCTION

One of the major tasks for the photovoltaic industry is to reduce cost per watt-peak. This can be achieved through lower production costs and higher efficiencies of photovoltaic modules. Thin film photovoltaics provide a promising way to reach this goal. However, in the production process of thin film solar cells a number of process- as well as material-induced electric defects can influence the conversion efficiency of thin film photovoltaic cells and modules.

One task is to control the position and the quality of the p-n junction. Therefore, a profound understanding and control of the p-n junction formation is required. In a previous publication we have shown that the p-n junction is often disturbed by structural defects [1]. Furthermore the p-n junction depth can also deviate from the ideal position at the front side of the solar cell leading to lower conversion efficiencies. Therefore, it is necessary to establish methods for an easy and fast determination of the p-n junction depth, ideally without destroying the solar cell by cross preparation.

In this contribution quantitative electron beam induced current (EBIC) measurements and EBIC imaging at cross sections have been applied at the same time to determine depth and quality of the p-n junctions from different thin film solar cell technologies.

2 SAMPLE PREPARATION AND EXPERIMENTAL METHODS

2.1 Sample preparation

The samples analysed in this contribution are

i. Si thin film technology: Two mini-modules using crystalline silicon on glass technology produced by CSG solar [2]. The mini-modules are normally illuminated through the glass. In case of this investigation the electron beam excites charge carriers from the back of the sample. Sample A has a glass/Si(n+/n-/p+) doping structure. Sample B has a glass/Si(n+/p-/p+) doping structure. Both samples are 2.1 µm thick. The highly doped emitter and back surface field regions are as deposited less than 100 nm thick each. Dopant diffusion during crystallization and annealing processes has intentionally been applied to move the p-n junction to different position in the samples A and B, respectively.
ii. CdTe thin film technology: The sample analyzed is a commercially produced CdTe thin film solar cell without the back-side glass. The investigated specimen is cut out of the whole module.
iii. CIGS thin film technology: The sample analyzed is a commercially produced CIGS thin film solar cell without the front-side glass. The investigated specimen is cut out of the whole module.

2.2 EBIC investigations on cross sections

The secondary electron microscopy (SEM) and electron beam induced current (EBIC) investigations were performed using a Hitachi SU70 equipped with an EBIC system from Point Electronics. The cross sections for SEM and EBIC investigations of the Si thin film samples were prepared using a bevel-polished cross-section preparation method. EBIC investigations at the CIGS and CdTe samples were performed by using Focus Ion Beam (FIB) and Ar ion cross section preparation (CSP) combined with EBIC measurements.

2.3 Acceleration voltage dependent EBIC investigations

Since the penetration depth of the electron beam in a specimen depends on the acceleration voltage E_b [3] a depth-resolved evaluation of the minority carrier collection efficiency can be performed. The EBIC current can be described as the depth integral of the product of the depth-dose function $g(x, E_b)$ [4] multiplied by the depth dependent collection probability $F(x)$:

$$I = \int_0^\infty g(x, Eb) F(x) dx \quad (1)$$

The maximum of the internal field gradient of the p-n junction can be derived using an iterative algorithm by Konovalov and Breitenstein. This iterative algorithm is explained in more detail elsewhere [5]. This method has been applied to determine non-destructively the p-n junction position. The samples need no further preparation steps except the contact preparation for top-view EBIC investigations.

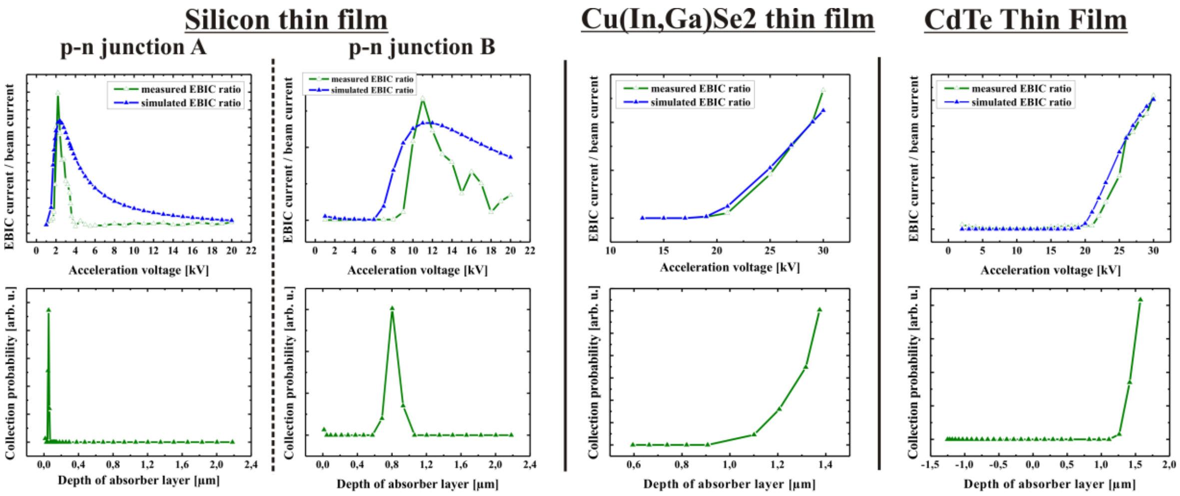

Figure 1: (upper line) Electron energy-dependent EBIC gain of measured (green line) and fitted (blue line) values. (lower line) Collection probability versus depth of the absorber layer derived from the fitted EBIC gain above.

3 RESULTS

3.1 Acceleration voltage dependent EBIC investigations

The measured depth-dependent EBIC current I_{EBIC} is divided by the measured beam current I_{beam} yielding an EBIC gain factor G which is independent of the beam current.

$$G = I_{EBIC} / I_{beam}$$

The measured EBIC gain factor for the three different solar cell technologies are shown as green lines in the upper line in Fig. 1 as a function of acceleration voltage of the electrons. Already at this raw data evaluation pronounced differences in the voltage-dependent EBIC gain factors of the different thin film solar cells can be observed indicating a variation of the p-n junction depth and sample structure. The fitted curve according to the theoretical model to the measured values is shown as blue lines for each thin film solar cell. The derived collection probability profiles calculated from the fitted EBIC gain profiles by means of the theoretical model of Konovalov and Breitenstein [5] are shown in the lower line of Fig. 1. The maxima of the collection probabilities correspond to the maxima of the field gradient in the depletion regions and thus to the position of the p-n junctions. Following results can be obtained:

(i) Si thin film p-n junction A: The maximum of the measured and simulated EBIC gain is at about 2.5 keV. Therefore, the maximum of the depletion region field gradient of p-n junction A as calculated from the fitted EBIC gain is about 90 nm beneath the surface. The peak is discrete and indicates a narrow p-n junction close to the surface. A deviation of the measured and fitted EBIC above 2.5 keV can be seen. The fitted values are lower than the measured EBIC gain values.

(ii) Si Thin Film p-n junction B: The maximum of the measured EBIC gain is at about 11 keV resulting in a p-n junction depth of about 850 nm beneath the surface. In contrast to p-n junction A, p-n junction B shows a broader peak with a smooth decrease above the peak at 11 keV indicating a wider p-n junction. The signal-to-noise ratio of this measurement is low. The fitted EBIC gain shows strong deviations to the measured values.

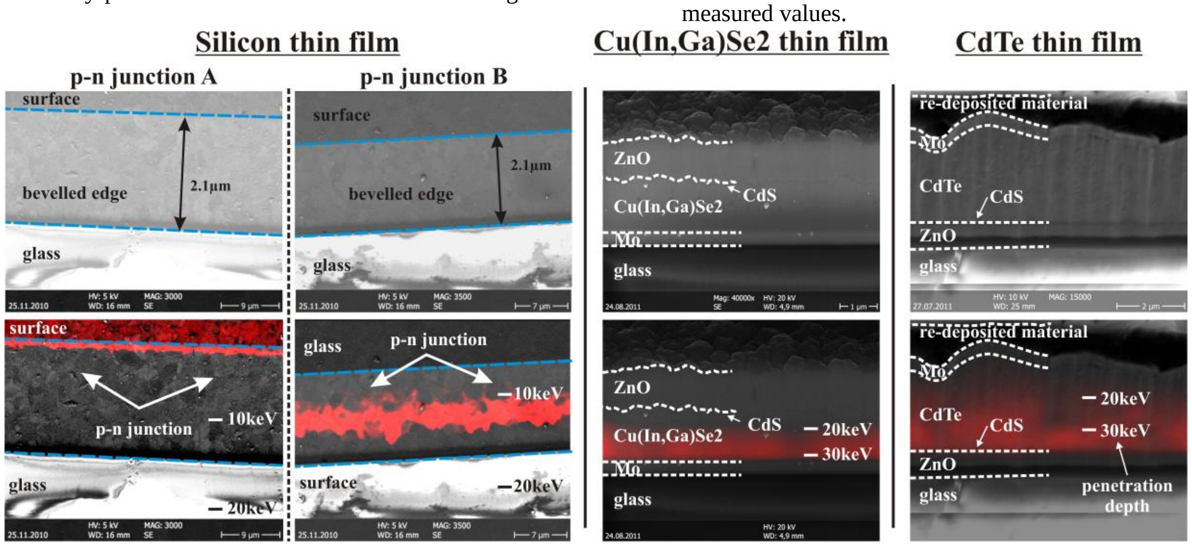

Figure 2: (upper line) SE images of the cross sections of the different thin film technologies. The different layers are enclosed by dotted lines. Note, the Si samples are bevelled cross sections. (lower line) SE images overlaid by EBIC measurements. The p-n junctions are clearly visible as regions with high EBIC signal (red colour).

(iii) $Cu(In,Ga)Se_2$ thin film p-n junction: Both, measured and fitted EBIC gain show a smooth increase from 20 keV up to 30 keV. Therefore a maximum cannot be distinguished. The deviation between the measured and fitted values is small. The collection probability increase from 1 µm to 1.4 µm referring to the absorber layer.

(iv) CdTe thin film p-n junction: Measured and fitted EBIC gain show a strong increase from 20 keV to 30 keV. The fitted values from 20 keV to 25 keV are slightly higher than the measured values. The collection probability increase from 1.3 µm to 1.7µm referring to the top of the absorber layer. Also in the CdTe thin film sample the maximum of the collection probability is not reached. .

3.2 EBIC investigations at cross sections

In order to evaluate the application potential and the reliability of the non-destructive method for thin film solar cells, cross sections have been prepared by mechanical polishing of the Si thin film samples, Focused Ion Beam (FIB) and Ar ion Cross Section Preparation (CSP) for the CIGS and CdTe samples. The SEM images of the cross sections of each thin film solar cell are shown in the upper line of fig. 2. The different layers and interfaces are marked by dashed lines. It should be noted that the Si layer appears in the SE image larger due to bevelled polishing. The Si layers are in both cases 2.1 µm thick. Fig. 2 (lower line) shows an overlay of the EBIC investigations (red color) and the SE image of the same areas as depicted in the upper line of Fig. 2. At the maximum of the field gradient of the p-n junctions the highest collection probability is observed resulting in a strong EBIC signal I_{EBIC} (red regions). Therefore, the positions of the p-n junctions are clearly visible in red colours. Following results can be obtained:

(i) Si thin film p-n junction A: Relating the lateral position of the p-n junction maximum to the width of the Si layer a junction depth of 90 nm can be calculated for p-n junction A. The p-n junction A is located close to the surface and obviously very sharp.

(ii) Si thin film p-n junction B: The p-n junction B is buried within the silicon layer at about 1 µm beneath the surface. Furthermore, a pronounced influence of the silicon thin film grain structure on the p-n junction is observed in sample B resulting in a broad p-n junction. A possible mechanism for influences of the p-n junction by defect structures is discussed in more detail elsewhere [6].

(iii) $Cu(In,Ga)Se_2$ thin film p-n junction: The region with high EBIC signal and therefore with high collection probability starts at about 0.8 µm and rises up to the Mo layer. An influence of defect structures cannot be observed.

(iv) CdTe thin film p-n junction: The region with high EBIC signal starts in the CdTe-layer at about 1 µm seen from the top of the CdTe-layer and ends at the TCO layer. The p-n junction seems to be very smooth and broad. The layer above the Mo-layer is re-deposited material caused by the CSP preparation method.

4 DISCUSSION

The deviation between measured and theoretical values for all samples is unexplained so far. The stronger drop of the measured EBIC gain compared to the simulated EBIC gain could be an indication to injection dependent defect properties therefore a saturation of recombination path may appear. Future applications of lock-in technologies will allow measurements at lower beam current in order to prove this assumption.

Aiming at a tool to evaluate the use for the non-destructive electron energy-dependent EBIC analysis we simulated the penetration depth of the electrons in the thin film solar cell by CASINO [7] and compared them with the electron energy-dependent EBIC gain measurements. In Fig. 2 the different penetration depths (90% of the electrons) are marked. For all thin film solar cells the CASINO simulation confirms the measured EBIC gain back. Therefore, it is possible to decide by a previous simulation, if an EBIC gain measurement is possible or not.

(i)+(ii) Si thin film samples:

The p-n junction depths determined at the bevelled cross sections are in a good agreement with the electron energy-dependent EBIC measurement of p-n junction A and B (cf. Fig. 1 and 2). P-n junction A is at about 90 nm and very sharp. In contrast to this p-n junction B is at about 1 µm beneath the surface and broad. This broad p-n junction is the reason for the broad collection probability peaks obtained by electron energy-dependent EBIC shown in Fig. 1. The p-n junction is strongly influenced by defect structures influencing the diffusion processes during p-n junction formation.

(iii) $Cu(In,Ga)Se_2$ thin film samples:

The EBIC gain increases from 20 keV up to 30 keV. No maximum of the collection probability can be detected by electron energy-dependent EBIC investigations therefore the position of the p-n junction cannot be determined. By using CASINO simulations [7] it is obviously that the electron penetration depth is not sufficient (see penetration depth in Fig. 2). Therefore higher electron acceleration voltages are needed to display the position of the p-n junction based on this method. No evidence to an influence of defect structures can be obtained. Also the measured and fitted EBIC gain values are in good agreement.

(iv) CdTe thin film samples:

The EBIC gain is increasing from 20 keV to 30 keV. Again, the p-n junction position cannot determine due to an insufficient penetration depth of the electrons which is also visible at the marked penetration depths in Fig. 2. The fitted and measured EBIC gain does not coincide from 20 keV to 25 keV. The EBIC investigation at the cross section indicates approximately in this penetration range an irregular p-n junction, possibly disturbed by defect structures.

Based on these initial application results we estimate that the depth resolution of this method is below 50 nm. A better signal-to-noise ratio could improve the results of the algorithm. Furthermore, the interpretation of the results may be influenced by defect structure properties. Please note that all results are under low injection conditions.

4 CONCLUSION

In various thin film solar cells (Si, CIGS, CdTe) the position and width of the p-n junction has been successfully determined by imaging EBIC at cross sections. A non-destructive determination of the p-n junction depth has been performed by electron energy-dependent EBIC measurements. Major prerequisite for non-destructive EBIC is a sufficient electron energy (> 30 kV for p-n junction depth of more than 2 µm). Based on the results it was shown that a CASINO simulation is useful to estimate the successful applicability of electron energy-dependent EBIC measurements. Also, the simulations and experimental results show that for routine EBIC applications (top-view) for photovoltaics an extended SEM electron acceleration voltage range will be required.

5 ACKNOWLEDGE

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