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DIFFUSION LENGTH MEASUREMENTS OF HETEROJUNCTION THIN FILMS BY JUNCTION-EBICG. JÄGER-WALDAU^{*,(1)}, D. SCHMID^{*} and A. JÄGER-WALDAU^{**}^{*}*Institut für physikalische Elektronik, Universität Stuttgart, Pfaffenwaldring 47, D-7000 Stuttgart, Germany*^{**}*Universität Konstanz, Fakultät für Physik, Postfach 5560, D-7750 Konstanz, Germany*

Abstract: Junction-EBIC is used to characterize minority carrier diffusion lengths in heterojunction thin films. Because the submicron diffusion lengths of our CuInSe₂-(Zn,Cd)S film devices and the diameter of the generation volume are in the same range, EBIC interpretation taking the generation volume as a point source is difficult. In our model we use a finite size of the generation volume to fit the EBIC measurements. It is possible to measure with a higher accelerating voltage and for that reason effects caused by surface recombination and high injection can be avoided. In this paper the model is described and experimental results are presented.

1. Introduction

The knowledge of the characteristic electrical properties is of fundamental interest for research and application of semiconductors. For instance the diffusion length L of the minority carrier is of major importance for the operation of solar cells. The determination of the diffusion length L by charge collection experiments in a scanning electron microscope (SEM) is one alternative to optical methods.

There are two excitation geometries to evaluate L values from electron beam induced current (EBIC) measurements in a SEM, junction-EBIC (JEBIC) and planar-EBIC (PEBIC). For JEBIC the solar cell is cleaved and the electron beam is scanned normal to the cross section. For PEBIC the beam is scanned perpendicular to the device surface.

PEBIC is the mostly used technique of these two methods. The theoretical model for this case is already established with the generation volume and the surface recombination velocity $1/\lambda$.

We used the JEBIC-mode because it is difficult to use the planar EBIC-mode to study polycrystalline heterojunction thin films if the thickness of the films (in our case $2\mu\text{m}$), the width of the generation volume and the diffusion length (L) have the same order of magnitude. These difficulties can be avoided by the use of junction-EBIC in linescan mode. In addition junction-EBIC allows to investigate the p-n junction in the whole area by different line scans.

2. Problem

For a quantitative interpretation of EBIC measurements the knowledge of the penetration range (R_G) of the electron beam into the material is necessary. The penetration range R_G can be calculated using the formalism of Everhart and Hoff [2]. But the common model for the analysis of junction-EBIC measurements is to presume the generation volume in the material to be a point source which is an inadequate simplification of the depth dose function $1/\lambda$. In our case of junction-EBIC on solar cells made of p-CuInSe₂ (absorber) and n-(Zn,Cd)S (window) we have to consider different penetration ranges in these two materials.

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Another problem is the surface of the sample. If the maximum of the depth dose function is about one diffusion length below the sample surface the EBIC signals are strongly effected by the surface recombination.

In addition high injection apparently decreases the measured diffusion length because of the high carrier density in the generation area at low accelerating voltages V_b . As mentioned by Matson /3/, the amount of generated electron-hole-pairs in the material by the electron beam is a linear function of the electron beam (I_b) (generation rate $G \sim I_b V_b$). The generation volume is proportional to R_G^3 assuming that the volume is almost a sphere and therefore proportional to V_b^5 (because $R_G \sim V_b^{1.7}$) /1/. Hence, the density of excess carriers is proportional to I_b/V_b^4 . The injected carrier density increases with decreasing V_b . And in the case of low-injection there should be a linear relation between I_{max} (maximum of the EBIC-signal) and the beam power, independent of the accelerating voltage. In figure 1 EBIC measurements are shown with different accelerating voltages as a function of the beam power $P = I_b V_b$.

Figure1: Maximum of the EBIC signal I_{max} versus beam power $P = I_b V_b$ with different accelerating voltages V_b of a standard coevaporated CuInSe_2 -(Zn,Cd)S device with about 10% efficiency.

In the case of high injection the density of free carriers in the space charge region (SCR) reaches the same order as the density of the fixed charges. Therefore the electrical field in the SCR and hence the current collection will be reduced and this can explain the deviation from the linear region. On the other side this deviation can not be explained by surface recombination, since the influence of the surface should not be correlated with the beam power. This is due to the fact that the size of the generation volume depends only on the beam voltage and not on the beam current (the ratio of the EBIC signals are different for different beam powers).

These two difficulties, high injection and surface recombination, can be avoided by performing the experiments under high accelerating voltages (25kV) and low beam currents so that the injection level is kept low (see Fig.1).

In this case the penetration range R_G is about $3.16\mu\text{m}$ in CuInSe_2 and $3.20\mu\text{m}$ in (Zn,Cd)S. Therefore the generation volume can no longer be assumed as a point source and the diffusion length can not be taken from a logarithmic plot of the EBIC linescan.

3. Theory

In addition to the depth dependend energy dissipation function /1/, Shea et al. /4/ derived a semi-empirical lateral dose function by the numerical integration over experimentally obtained generation volumes. This function is analog to the depth-dose function.

In our model we used the following equation for the generation rate $g(x)$ as a function of the distance x from the impinging center x_0

$$g(x) = g_0 * \exp \frac{-|x-x_0|}{0.25 R_G}$$

g_0 : normalization factor

which is an approximation of the semiempirical lateral dose function.

Fig.2: Lateral dose function by Shea /4/.

Normalized lateral energy dissipation versus distance x/R_G from the beam center and the approximation used for our model.

The use of this generation function led to an error smaller than 6% made by the underestimation of the generation for $x < 0.1R_G$ whereas the error for overestimating the generation for $x > 0.6R_G$ is about 2.5%. The generation function was used in the continuity equation for our calculations:

$$D_p \frac{d^2 p}{dx^2} - \frac{p-p_n}{\tau_p} + g(x) = 0 \quad \text{diffusion region (DR)}$$

$$g(x) + \frac{1}{e} \frac{di_n}{dx} = 0 \quad \text{space charge region SCR}$$

with D_p diffusion-coefficient, p minority charge carrier, τ_p lifetime of the carrier, i_n induced current

for p-type material. In n-type material analogous equations are used.

This differential equation has to be solved depending whether x_0 is in the n- or p-type region, in the space charge region or in the diffusion region. As boundary conditions we assumed the excess carrier density to be zero at the edge of the space charge region (SCR) and at infinity.

With this model the influence of the surface recombination can be neglected because the accelerating voltage can be increased and so the generation volume is deep enough in the material. The generation volume is growing proportional to the fifth power of the accelerating voltage whereas the number of generated carriers is directly proportional to the beam power. Due to these facts the carrier density decreases with increasing accelerating voltage. As a result the danger of high-injection is avoided.

We want to explain our calculations of junction EBIC measurements on solar cells by means of the following figure 3.

The whole modellized EBIC signal is depicted in curve A. The curves B,C,D,E represent the signals from different irradiation regions. The influence of the expansion of the generation volume can be seen for example in the diffusion region of the n-type material. It is detected an EBIC-signal in the n-type diffusion region, though the electron beam irradiates the p-type part of the SCR.

Figure 3: The parts of our model according to the different regions of the samples.

A: the whole theoretical EBIC signal; B: signal from the p-type material without the SCR; C: signal from the part of the SCR in the p-type material; D: signal from the part of the SCR in the n-type material; E: signal from the n-type material without the SCR

Figure 4 shows the influence of the different materials. For the simulation we varied the portion of the space charge region to the n-type and p-type material. For curve A the part of the space charge region in the n-type material was about 10%. When we shift this part further to the n-type side we can obtain a hump in the signal. The reason for this hump is the difference in the band-gaps of the materials. The band-gap of CuInSe_2 is $E_g = 1.04\text{eV}$ whereas for $(\text{Zn,Cd})\text{S}$ it is $E_g = 2.6\text{eV}$. Therefore in the n-type material the electron beam will generate 2.5 times less electron-hole-pairs as in the p-type material. So the EBIC-signal will differ by the same factor.

Figure 4: Simulated variation of the width of the space charge region in the p- or n-type material.

4. Results

With our model we calculated EBIC-signals with different diffusion length as given parameters (Fig.5). When we analyse the slope of these calculated signals in a logarithmic plot, all values of these slopes are equal and represent the slope of the generation volume ($R_G/4$) - not the diffusion length. This happens if R_G is greater than four times the diffusion length. Figure 5 shows the results from a simulation.

Figure 5: Logarithmic plot of EBIC signals versus the distance calculated by the model.

If we are measuring the penetration range R_G by evaluating the slope of the EBIC-signals at the highest accelerating voltages of 39kV (maximum of our SEM) we can compare them with the results calculated with the theory of Everhart and Hoff [2]. The differences between our measurements (Fig.6) and the calculation can be explained by the fact that the weight densities are different in the polycrystalline and in the single crystal material (single crystal values were taken for the theoretical calculations).

Figure 6: Curve A: EBIC linescan recorded at $V_b = 39\text{kV}$. The Grün ranges are evaluated from the slopes.

Curve B: EBIC linescan at 25kV (hollowed circles) and calculated model with least square fit (solid line). $L_n = 0.65 \mu\text{m}$, $L_p = 0.44 \mu\text{m}$, $W_p = 0.89 \mu\text{m}$

As well measurements at high accelerating voltages (39kV) are possible, but for the resolving power in the sample lower voltages are more favourable. So we had to take a compromise solution. Therefore we used an accelerating voltage of 25kV.

In figure 6 also a measured junction-EBIC linescan is given. The calculated and extracted results by the fit from the theoretical model to the measured signal for the diffusion length are $L_n = 0.65 \mu\text{m}$ in CuInSe_2 (p-type) and $L_p = 0.44 \mu\text{m}$ in the n-type material (Zn,Cd)S. The space-charge-region width is about $W_p = 0.89 \mu\text{m}$ in the absorber.

In other measurements similar results of the extracted values were obtained, too. Also the behaviour for voltage dependent space charge regions were noticed but not calculated (not possible with our simple model). Scheer /5/ reported a diffusion length in the range of $1\text{ }\mu\text{m}$ in n-CuInSe₂ measured with PEBIC. Matson also measured the diffusion lengths in CuInSe₂ with the EBIC mode, but with single crystals. His highest values were about $2.8\text{ }\mu\text{m}$.

For lower beam voltages the influence of the surface recombination decreases the diffusion lengths from the experiment. In table I the values of the diffusion length measured at different accelerating voltages are given. The measurements were performed in the low injection case, so the results depend only on the surface recombination of carriers outside the SCR. Therefore, measurements recorded at low accelerating voltages are not allowed to calculate the diffusion length with our model.

Table I: Diffusion length L measured for increasing accelerating voltages. The surface influence is decreasing.

V_b/kV	10	15	20	25
$L/\mu\text{m}$ (CuInSe ₂)	0.24	0.41	0.57	0.65
$L/\mu\text{m}$ ((Zn,Cd)S)	0.10	0.22	0.36	0.44

With the numerical model the charge collection efficiency η can also be extracted. For heterojunctions the efficiency η can not be calculated using the equation

$$\eta_{EBIC} = \frac{I_{EBIC}}{e g_0} \quad g_0 = \frac{V_b I_b}{E_{eh}} (1-f)$$

and setting $I_{EBIC} = I_{max}$ (g_0 generation rate, E_{eh} electron hole pair creation energy, f electron back-scattering fraction) /6/. This leads to an error since E_{eh} and f are different in both semiconductors. To get more accurate values for η we calculated it also in our fit. The highest obtained collection efficiencies were about 70%. Interface recombination as well as the backscattering factors, the creation energy for the electron hole pairs etc. might be reasons why a maximum of 100% was not reached.

5. Conclusion

The usual model to fit EBIC measurements was further developed for the case of a finite generation volume. This model was applied to our junction-EBIC measurements on CuInSe₂-(Zn,Cd)S solar cells using high accelerating voltages in order to avoid the high injection condition and influences of surface recombination. From our experiments the penetration range R_G , the minority carrier diffusion length L_n and L_p and the width of the space charge region W_{SCR} can be extracted.

6. References

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