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DIFFUSION LENGTH MEASUREMENT USING THE SCANNING ELECTRON MICROSCOPE

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DIFFUSION LENGTH MEASUREMENT USING THE SCANNING ELECTRON MICROSCOPE

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SUMMARY

A measurement technique employing the scanning electron microscope is described in which values of the true bulk diffusion length are obtained. It is shown that surface recombination effects can be eliminated through the application of highly doped surface field layers. The influence of high injection level effects and low-high junction current generation on the resulting measurement is investigated. Close agreement is found between the diffusion lengths measured by this method and those obtained using a penetrating radiation technique.

INTRODUCTION

The determination of bulk diffusion lengths in semiconductor devices is a difficult process. Until recently, techniques have been employed to measure this parameter, there is a serious lack of agreement between the values obtained by various methods.

One of these techniques, involving the use of the scanning electron microscope (SEM) electron beam to generate carriers in a sample containing a collecting junction, has been employed by several investigators (1, 2). In this technique, the diffusion length is determined by measuring the variation of the short circuit current as the location of the injecting beam is moved with respect to the collecting junction. The main difficulty with this type of measurement is that carrier recombination at the beam entry surface must be accounted for (3). This puts severe limitations on the use of the method, especially for devices which have dimensions comparable with a diffusion length. Furthermore, surface recombination effects induced by the injecting electron beam on P-type material make this technique extremely difficult to apply to P-based devices of moderate to high resistivity, that is, $\rho \geq 10$ ohm-cm. Elimination of the influence of these surface effects would greatly simplify these measurements.

A SEM technique has been developed here in which surface recombination is effectively controlled by the application of highly doped surface field layers to the samples being investigated. Furthermore, the application of the field layer not only reduces surface recombination but also prevents the occurrence of beam-induced inversion layer effects, permitting measurements to be made on P-based as well as N-based devices. Because of the geometry involved and the large magnitudes of diffusion length usually found therein, the method is ideally suited for measurements in silicon solar cells.

It is the purpose of this paper to describe this technique and to compare the results to those obtained by an independent technique in which penetrating radiation (X-rays) is used for carrier generation. The means for obtaining the necessary values of surface recombination velocity are described as are the effects of factors such as injection level and current collection from a low-high junction. It should be brought out that the technique described here is limited to cells which contain a back surface field layer. Also, the theoretical treatment must be modified to include low-high junction current contributions if cells with base resistivity higher than 10 ohm-cm are to be investigated.

DEVELOPMENT OF TECHNIQUE

Theory

Let us consider injection of carriers by the SEM beam at a point just inside the rear face of a silicon solar cell. The cell is assumed to be a planar device with lateral dimensions very much larger than a diffusion length. The fraction of the injected carriers that is collected by the junction is directly related to the diffusion length. The collected fraction is, however, sensitive to the recombination velocity at the beam entry surface. These points are brought out by the following analysis.

The continuity equation describing point injection of carriers in a planar solar cell of thickness $d$, at a distance $x_1$ from the collecting junction is

$$\nabla^2 n = \frac{\mu_e E}{L^2}$$

where $L$ is the bulk diffusion length. The solution of Eq. (1) under the boundary conditions:

1. At the junction, $x = 0, n = 0$
2. At the rear face, $x = d$, $\frac{dn}{dx} = 0$

yields an expression for the short circuit current

$$I_{sc} = \frac{I_{max}}{1 + \frac{(L - s)}{1 + s} \exp y_1} \left( \frac{1 - s}{\exp y_2} \right) \left( \frac{1 + \frac{(L - s)}{1 + s} \exp y_1}{\exp y_2} \right)$$

where $y_1 = (d - x_1)/L$, $y_2 = -x_1/L$, $I_{max}$ is the carrier generation rate times the unit charge, and $s = SL/D$ where $S$ is the surface recombination velocity and $D$ is the minority carrier diffusion coefficient.

Now consider generation of carriers just inside the rear surface of the cell. By setting $x_1 = d$ in Eq. (1), the family of curves shown in Fig. 1 can be obtained. Here, $I_{sc}/I_{max}$, the fraction of the injected carrier flux which is collected by the junction, is plotted as a function of $d/L$. Once values of $I_{max}$ and $s$ have been determined, L can be obtained from the measured value of $I_{sc}$.
Apparatus

A JEOL JSM-2 scanning electron microscope was used in these investigations. To permit SEM electron beam entry into the rear of the cell, a small (1 mm × 1 mm) window was chemically etched in the back contact metallization exposing the P*/ layer. The beam current was measured by means of a Faraday cup mounted on the specimen holder.

I<sub>max</sub> Determination

I<sub>max</sub> can be determined theoretically from the known pair production energy (3.5 keV for silicon (4)), the incident beam energy (40 keV used in this work), the electron back-scattering coefficient (0.16 for 40 keV electrons normally incident on silicon (8)), and the incident beam current, I<sub>B</sub>. Using these values the following relation is obtained:

I<sub>max</sub> = 9.6 × 10<sup>3</sup> I<sub>B</sub>

The calculated value was verified experimentally from I<sub>Isc</sub> measurements when the carriers were injected in close proximity to the junction where the collection efficiency is expected to approach 100 percent. Agreement was found to within 0.5 percent.

Surface Recombination Velocity

As can be seen from Fig. 1, l<sub>Isc</sub>/I<sub>max</sub> decreases rapidly as s increases. In order to use Eq. (1) to determine L, we must know s. Furthermore, because of noise considerations, the lower the value of s, the greater the ease and accuracy of the measurements.

A highly doped field layer applied to the rear surface of a solar cell is known to reduce s at the rear face of the cell to low values (8). Hence it is logical to make use of the field layer in the present measurements to effect the desired reduction in s.

Although it is known that s is reduced by the addition of a field layer, uncertainty exists as to the quantitative nature of the reduction. An experiment was devised, therefore, to determine the degree of reduction in s effected by the addition of the field layer. Performed on P-base cells of special geometry, the experiment is essentially a measurement of short circuit current as a function of cell thickness. The cells were fabricated such that they contained crescent-shaped slots, 1 mm wide and about 1 cm in length, cut in their rear faces (Fig. 2). Cell thickness at the bottom of the slot was of the order of 25 μm. The geometry selected permits the measurement of the variation of I<sub>Isc</sub> with cell thickness without the interference of edge effects which could be present if an angle-lapped geometry were used. After slotting, the P*/ layer was incorporated by evaporating several micrometers of aluminum on the rear surfaces and diffusing at 875°C for 60 minutes. Subsequently to the diffusion step, the remaining aluminum was removed from the slot and a small adjacent area to permit entry of the electron beam.

Measurements of I<sub>Isc</sub>/I<sub>max</sub> were then made as a function of position as the electron beam traversed the length of the slot. The resulting data were then used with Eq. (2) to determine the surface recombination velocity on the rear surface of the cell.

High Injection Level Effects

Measurements of the current gain, that is, the ratio of the collected current to input beam current, were made to determine the possible influence of high injection level effects on the measured short circuit current.

Low-High Junction Effects

A low-high junction is formed near the rear face of a cell upon the application of a highly doped field layer (7). Although this type of junction repels minority carriers it is a collector of majority carriers. Thus it is expected that such a junction would produce a photo current and a photovoltaic through the collection of excess majority carriers. Contributions from this junction to the measured short circuit current must be taken into account in the theoretical model used. A pair of experiments were performed, therefore, in an attempt to detect possible low-high junction current generation.

Comparison to X-Ray Measurements

Since agreement with the results of an independent method would be verification of the present method, a comparison was made between the results of the SEM measurements on a number of 10 ohm-cm N*PP + BSF solar cells with the values of I<sub>L</sub> determined by a penetrating radiation technique employing X-rays as carrier generators. The details of the X-ray technique, which has been used at this laboratory for several years, are presented elsewhere (8, 9).

RESULTS AND DISCUSSION

Surface Recombination Velocity

Results of the measurement of I<sub>Isc</sub>/I<sub>max</sub> as a function of the location of carrier injection along the slot in one of the specially fabricated cells is shown in Fig. 4. As can be seen, I<sub>Isc</sub>/I<sub>max</sub> drops sharply as the injecting beam begins to impinge on the slotted area, indicating a higher value of s in the slot than on the flat, unslotted region. The increase in s is probably due to residual lattice damage from the slot grinding procedure.

The scatter in the data in Fig. 4 is believed due to the presence of tenacious aluminum-silicon alloy particles remaining on the surface which reduce the magnitude of the
beam current that enters the underlying silicon. Thus the
true response of the uncovered silicon is best described by
the upper envelope of the data.

The best fit of Eq. (2) to the data along the slotted region
is indicated by the solid curve in Fig. 4. The theoretical fit
requires a value of $s = 0.315$ for $a$ and a value of $295 \mu$m for $L$.
This value of $L$ can then be used with Eq. (2) to determine $s$
on the flat, unslotted region. The results of such a calculation
indicate that on the flat area, $s = 0.612$. Upon trans-
slating these numbers to absolute values one finds recombinations
velocities of ~400 cm/sec in the slot and ~15 cm/sec on
the flat. The latter value is several orders of magnitude
less than the minority carrier diffusion velocity. This
means that, for all practical purposes, the $P^+$ field layer
as described above constitutes a perfectly reflecting barrier
to minority carrier transport, effectively preventing re-
combination at the rear surface of the cell.

High Injection Level Effects

Measurements of the current gain as a function of beam
current were made for beam currents that ranged from a few
picoamperes to over a nanoampere for a wide range of de-
focusing conditions. No variation in the gain with beam current
was observed, indicating that the measurements are free of high injection level effects.

Low-High Junction Effects

The PN junctions were removed from a number of
10 ohm-cm $N^+PP^+ B'F$ cells, isolating the $PP^+$ junctions.
$V_{oc}$ measurements on the isolated junctions under roughly
simulated AMO conditions show that no significant voltage is
produced when this material is used, that is, $V_{oc} \approx 0.005$
volts. Similarly treated 100 ohm-cm cells, however, yielded
open circuit voltages of 0.050 to 0.100 volt.

In a second experiment, the backs of several cells were
divided into two regions, as previously described (Fig. 3). For 10
ohm-cm cells, no increase in $I_{oc}$ was found when the
injecting beam was switched from the open circuited side
to the metered side, whereas for 100 ohm-cm cells a signif-
ificant ~8 percent increase was observed. These results are
consistent with the $V_{oc}$ measurements on isolated $PP^+$
junctions.

We can conclude, therefore, that for cells of 10 ohm-cm
base resistivity, $PP^+$ current generation through the collection
of excess majority carriers is not a concern.

Comparison to X-Ray Measurements

A comparison of the results of the SEM measurements
with the values of $L$ determined by the X-ray technique is
shown in Fig. 5. As seen in Table 1, there is a good cor-
relation between the results of the two techniques. The two
methods agree to within a multiplicative factor, the SEM
lengths being consistently about 1.9 times greater than those
determined by the X-ray method.

The fact that there is a linear relationship between the results
of these two basically different techniques, indicates the essential validity of both materials. A calibration
error is indicated, however, in one or both methods.

Because the point injection method yields an absolute
value of $L$ from a knowledge of a few easily determined pa-
rameters, while the X-ray technique depends upon rather
complex assumptions as to the carrier generation rate, it
appears more likely that the discrepancy can be attributed to a
miscalibration of the X-ray method. This hypothesis is
supported by the results of short circuit measurements made
in the X-ray apparatus on back surface field cells before and
after removal of the field layer. In all cases the $I_{sc}$ drops
observed upon the removal of the $P^+$ layer exceeded those
expected under the original calibration conditions. For
example, Table 1 gives the observed $I_{sc}$ drops, the expected
drops under the original calibration, and the expected drops
if the X-ray apparatus were recalibrated to agree with the
SEM results, for cells with both aluminum and boron field
layers. The values of the expected drops were obtained from
the appropriate $I_{sc}$ versus $L$ curve (3), assuming an
$s = 0$ back contact for the cell in the SIN condition and an
$s = 10^6$ cm/sec back contact for the $P^+$-removed condition.

The fact that the measured drops are larger than those
predicted under the original calibration indicates that the
X-ray apparatus is indeed miscalibrated and will yield errone-
ously low values of $L$. The recalibration scheme, on the
other hand, predicts values that are consistent with the ex-
perimental data. It follows, then, that a recalibration of the
X-ray method as dictated by the data in Table 1 will essen-
tially eliminate the discrepancies between the two techniques.

CONCLUSIONS

The results of these investigations into the use of
the scanning electron microscope to measure bulk diffusion
lengths can be summarized as follows:

(1) A technique for determining bulk diffusion lengths in
silicon solar cells has been developed which yields an abso-
lute value of $L$ from a knowledge of only the cell thickness
and the collected fraction of the injected carrier flux.

(2) This technique requires a means of reducing $\tau$
minority carrier recombination velocity at the rear face.
It has been shown that the addition of a highly doped field
layer to the rear surface of a 10 ohm-cm cell reduces the
minority carrier recombination velocity there to negligible
values.

(3) High injection level effects do not influence the results
of this technique under normal operating conditions, that is,
40-kev electrons at beam currents less than $1 \times 10^{-5}$ ampere.

(4) For base resistivities of 10 ohm-cm or less, contri-
butions to the measured short circuit current due to majority
carrier collection at the low-high junction formed by the addi-
tion of the field layer at the rear surface have been shown to
be negligible. In order to use higher base resistivity cells,
however, contributions from the low-high junction must be
taken into account.

(5) Close agreement has been shown between the results
of this technique and those obtained by a penetrating radiation
(X-ray) technique. The diffusion lengths determined by these
methods are found to be significantly larger (~1.9 x) than
Table 1.

<table>
<thead>
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<th></th>
<th>Observed $I_0$ (μA)</th>
<th>Original calibration $I_0$ (μA)</th>
<th>New calibration $I_0$ (μA)</th>
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<tr>
<td>363-5</td>
<td>BF</td>
<td>27</td>
<td>132</td>
</tr>
<tr>
<td>21.6</td>
<td>BF</td>
<td>60</td>
<td>182</td>
</tr>
<tr>
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<td>non BF</td>
<td>26.5</td>
<td>90.7</td>
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<tr>
<td>HAL-25</td>
<td>BF</td>
<td>55.7</td>
<td>410</td>
</tr>
<tr>
<td>22.6</td>
<td>non BF</td>
<td>22.6</td>
<td>55.7</td>
</tr>
<tr>
<td>33.6</td>
<td>non BF</td>
<td>33.6</td>
<td>65.7</td>
</tr>
</tbody>
</table>

previous measurements indicate. The cause of this difference was shown to be an apparently erroneous calibration of the X-ray technique.

REFERENCES

Figure 1. - A plot of the collected fraction of injected carriers as a function of the ratio \( \frac{d}{L} \).

Figure 2. - Schematic diagram of slotted cell.

Figure 3. - Schematic diagram of split-back configuration.

**ORIGINAL PAGE IS OF POOR QUALITY**
Figure 4 - A plot of the collected fraction of injected carriers as a function of distance across back of cell.

Figure 5 - A comparison of diffusion lengths measured in the SEM with those measured with penetrating radiation.