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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. While many techniques have been employed to measure this parameter, there is a serious lack of agreement between the values obtained by the 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 inversion effects induced by the injecting electron beam on P-type material make this technique extremely difficult to apply to P-base 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-base as well as N-base 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_i from the collecting junction is

$$\nabla^2 n(x) - \frac{n(x)}{L^2} = 0 \qquad (1)$$

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, $x = d$, $D(dn/dx) = Sn$

yields an expression for the short circuit current

$$I_{sc} = I_{max}\left[\frac{1 + \left(\frac{1-s}{1+s}\right)\exp 2y_1}{\exp y_2 + \left(\frac{1-s}{1+s}\right)\exp y_2 \exp 2y_1}\right] \qquad (2)$$

where $y_1 = (d - x_i)/L$, $y_2 = -x_i/L$, I_{max} is the carrier generation rate times the unit charge, and $s = SL/D$ where S is the rear 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 $x_i = d$ 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_{max} Determination

I_{max} can be determined theoretically from the known pair production energy (3.5 ev for silicon (4)), the incident beam energy (40 kv used in this work), the electron backscattering coefficient (0.16 for 40 kv electrons normally incident on silicon (5)), and the incident beam current, I_B. Using these values the following relation is obtained:

$$I_{max} = 9.6 \times 10^3\, I_B$$

The calculated value was verified experimentally from I_{sc} 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, I_{sc}/I_{max} decreases rapidly as s increases. In order to use Fig. 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 (6). 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 studied 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_{sc} 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. Subsequent 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_{sc}/I_{max} 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 photovoltage) 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.

(1) Open circuit voltage measurements were made on isolated PP^+ low-high junctions.

(2) The rear faces of a number of 10 ohm-cm and 100 ohm-cm N^+PP^+ BSF cells were divided into two regions by etching grooves across the rear faces of the cells (Fig. 3). The I_{sc} was then measured (in the SEM) from one of the rear areas while carriers were injected first into one of the areas and then into the others. An increase in I_{sc} when injection takes place on the metered side would be an indication of current generation at the PP^+ junction.

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 BSF solar cells with the values of L 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_{sc}/I_{max} 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_{sc}/I_{max} 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 0.315 for s and a value of 262 μm 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, $s = 0.012$. Upon translating these numbers to absolute values one finds recombination 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 here constitutes a perfectly reflecting barrier to minority carrier transport, effectively preventing recombination 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 defocusing 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^+ BSF 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, $V_{oc} \leq 0.005$ volt. 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_{sc} was found when the injecting beam was switched from the open circuited side to the metered side, whereas for 100 ohm-cm cells a significant (~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. 6. As seen in the figure [illegible] a good correlation between the results of the [illegible]niques. 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 calibrational 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 parameters, 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 curves (9), assuming an $s = 0$ back contact for the cell in the BSF condition and an $s = 10^8$ 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 erroneously low values of L. The recalibration scheme, on the other hand, predicts values that are consistent with the experimental data. It follows, then, that a recalibration of the X-ray method as dictated by the data in Table 1 will essentially 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 determing bulk diffusion lengths in silicon solar cells has been developed which yields an absolute 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 the minority carrier recombination velocity at the cell 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 1×10^{-9} ampere.

(4) For base resistivities of 10 ohm-cm or less, contributions to the measured short circuit current due to majority carrier collection at the low-high junction formed by the addition 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

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

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Table 1.

		Observed I_{sc} (μa)	Original calibration		New calibration	
			L(μ)	I_{sc} (μa)	L(μ)	I_{sc} (μa)
362-5 (Boron)	BSF	27	60	27	152	27
	non BSF	21.5	60	26.5	152	20.7
HAL-25 (Aluminum)	BSF	55.7	215	55.7	410	55.7
	non BSF	29.9	215	33.5	410	28.1

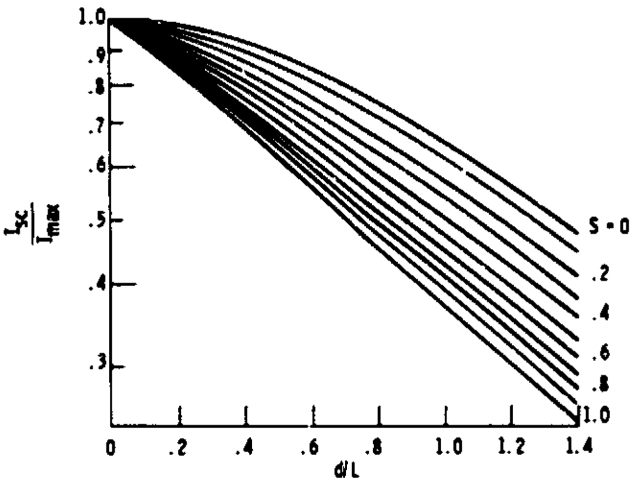

Figure 1. - A plot of the collected fraction of injected carriers as a function of the ratio d/L.

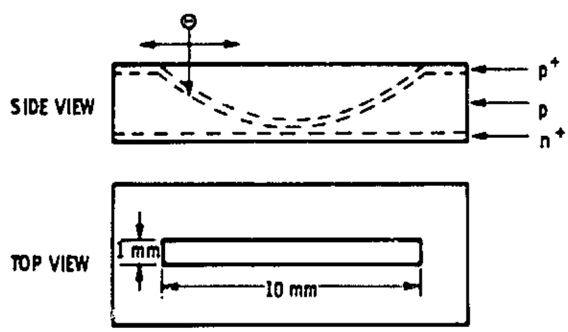

Figure 2. - Schematic diagram of slotted cell.

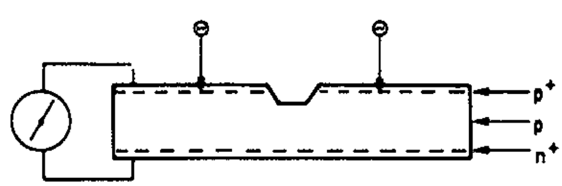

Figure 3. - Schematic diagram of split-back configuration.

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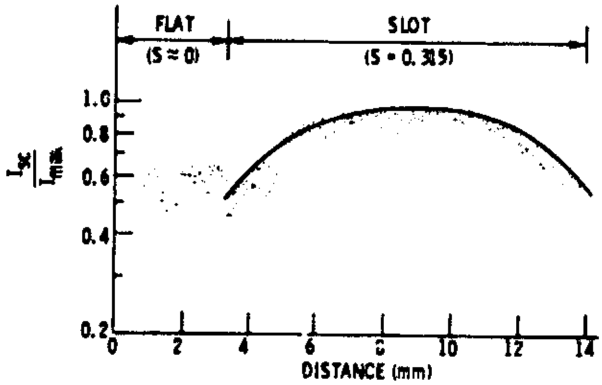

Figure 4. - A plot of the collected fraction of injected carriers as a function of distance across back of cell.

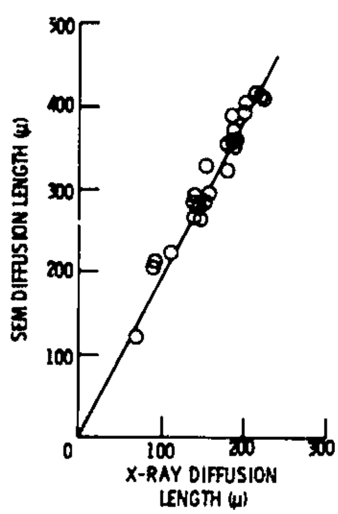

Figure 5. - A comparison of diffusion lengths measured in the SEM with those measured with penetrating radiation.