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A new method for the measurement of series resistance of solar cells

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Abstract. A method is proposed which uses the observed nonlinearity in the short-circuit current versus light intensity curve, at high intensities, to determine the series resistance of solar cells.

In this paper a new method for measuring the series resistance of a solar cell is proposed. The I–V characteristics of a solar cell under illumination can be written in the form (Wolf and Rauschenbach 1963)

$$I = I_{\mathrm{L}} - I_0 \left[\exp\left(\frac{q(V+IR_{\mathrm{s}})}{AkT}\right) - 1\right] \tag{1}$$

where I_{L} is the light generated current, R_{s} is the lumped series resistance of the solar cell and other symbols have their usual meaning. In the short-circuit configuration $V=0$ and equation (1) reduces to

$$I_{\mathrm{sc}} = I_{\mathrm{L}} - I_0 \exp\left(qI_{\mathrm{sc}}R_{\mathrm{s}}/AkT\right) \tag{2}$$

where I_{sc} is the short-circuit current in the cell and the unity in the square brackets has been neglected. From equation (2) it can be seen that if $I_{\mathrm{sc}}R_{\mathrm{s}}$ is negligible, I_{sc} varies linearly with intensity of illumination. This is the usual case at low intensities of illumination. However, as the intensity of illumination is increased I_{sc} increases, the term I_0 exp $(qI_{\mathrm{sc}}R_{\mathrm{s}}/AkT)$ is no longer negligible in comparison to I_{L}, and I_{sc} varies nonlinearly with intensity. The deviation from linearity is a manifestation of the series resistance and can be used to determine the value of series resistance.

Rearranging equation (2) we obtain

$$\ln\left[(I_{\mathrm{L}} - I_{\mathrm{sc}})/I_0\right] = qI_{\mathrm{sc}}R_{\mathrm{s}}/AkT. \tag{3}$$

We can see from equation (3) that the plot of ln $(I_{\mathrm{L}} - I_{\mathrm{sc}})$ versus I_{sc} will be a straight line with a slope $s = qR_{\mathrm{s}}/AkT$. If the diode factor A is known, R_{s} can be calculated from the slope s.

Using the method explained above, we have determined the value of R_{s} for space quality $\mathrm{n^+p}$ (2 cm × 2 cm) Si solar cells fabricated at the Solid State Physics Laboratory (Delhi). The light source used was an AMO simulator from the Schoffel Corporation (USA). The intensity of illumination was varied by varying the distance between the

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light source and the cell. The temperature of the cell was maintained constant with a cryostat. A compensated calibrated thermopile from Kipps and Zonen (Holland) was used, with the neutral density filters, to measure the intensity of light incident on the cell.

The measured values of I_{sc} have been plotted as a function of the incident light intensity in figure 1. We see from figure 1 that I_{sc} is linear with I_L up to about 500 mW cm^{-2}. However, in figure 1, the departure from linearity becomes apparent only beyond about 700 mW cm^{-2}.

As we have discussed earlier, in the linear region $I_{sc} \simeq I_L$. Since I_L always varies linearly with intensity (Wolf and Rauschenbach 1963), the extrapolated linear region

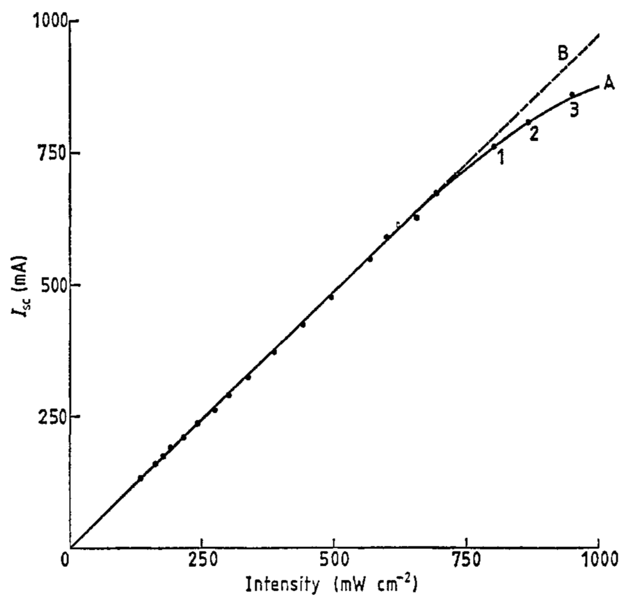

Figure 1. Measured values of short-circuit current I_{sc} (curve A) plotted as a function of intensity of illumination. The dashed curve (curve B) corresponds to I_L extrapolated from the linear region of I_{sc}. Points 1–3 refer to figure 2.

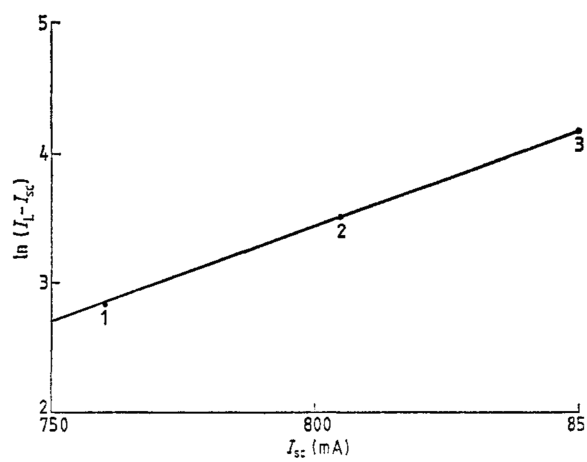

Figure 2. Ln $(I_L - I_{sc})$ as obtained from figure 1 plotted as a function of I_{sc}. The points correspond to the numbered points in figure 1.

represented by the dashed curve in figure 1 gives I_L. From these two curves ln $(I_L - I_{sc})$ is calculated, and is plotted as a function of I_{sc} in figure 2. We see that the plot is a straight line and agrees with the theory. The value of A is determined (Neugroschel *et al* 1977) from dark-forward characteristics of the cell and was found to be equal to 1. The value of R_s determined from the slope of the plot in figure 2 was found to be 0.38 Ω. This value was found to agree with the value obtained from other methods (Imamura and Portscheller 1970).

We shall now discuss the relative merits of our method in comparison to other methods for measuring R_s. We consider the following three well known methods: (i) the illuminated curve method (Wolf and Rauchenbach 1963); (ii) the p–n junction–dark-forward characteristic method (Imamura and Portscheller 1970); and (iii) the method due to Rajkanan and Shewchun (1979). In (i) the whole of the I–V characteristic has to be measured at two different intensities. In (ii) I_{sc} and V_{oc} have to be measured at different light intensities along with the dark-forward characteristics corresponding to each V_{oc}. This method actually yields R_s in the dark mode of solar cell operation. In (iii) V_{oc}, I_{sc} and the dark diode voltage corresponding to each I_{sc} have to be measured at different light intensities.

In contrast to these methods, our method requires the measurement of a single parameter I_{sc} as a function of light intensity and is therefore quicker and more accurate. We do need to know the value of the diode factor A, which is usually available from independent measurements or can be obtained quite accurately by measuring the dark-forward characteristic of the solar cell. It may be remarked that in our method it is not necessary to measure the absolute values of the light intensity: it would suffice to vary the incident light intensity by a known ratio, such as by using the neutral density filters.

In all the other three methods given above, it has been assumed that $I_{sc} = I_L$. This assumption is valid only at low light intensities, as is well known and is apparent from figure 1. Our method, on the other hand, depends upon the departure of I_{sc} from I_L at high intensities. Since the effect of R_s on the performance of a solar cell is important only at high intensities, our method has the advantage of giving R_s in such operating conditions. Our method of course cannot be used to give R_s at low intensities. This method can therefore be used to supplement the information about R_s obtained by other methods at low intensities.

The chief disadvantage of our method is that measurements have to be made over a wide range of intensities from low intensities where $I_{sc} = I_L$ to high intensities where the departure of I_{sc} from linearity becomes substantial. If the value of A over this range is not constant, it would introduce nonlinear behaviour in the ln $(I_L - I_{sc})$ versus I_{sc} plot. The nonlinearity in this plot may also be caused by the dependence of R_s on the light intensity. Thus our method will not be reliable in a region of intensity where ln $(I_L - I_{sc})$ has a nonlinear dependence on I_{sc}, but has the advantage of immediately displaying the intensity dependence of R_s and/or A. In the present case, as shown in figure 2, ln $(I_L - I_{sc})$ is found to be linear with respect to I_{sc} until at least 1000 mW cm^{-2}, and therefore the measured value of R_s should be quite reliable.

However, at high illumination levels the depletion layer width changes due to voltage drop $(I_{sc}R_s)$ across the p–n junction and I_{sc} may vary nonlinearly with I_L. We have made detailed numerical calculations using equations (1), (2) and (3) of Agarwala *et al* (1980). These calculations show that even at the highest illumination levels used in our experiments, the change in total I_{sc} due to the change in the width of the depletion layer is less than 0.2% and so can be neglected.

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