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Measurement of solar cell parameters using impedance spectroscopy

M.S. Suresh

Battery Division, ISRO Satellite Centre, Airport Road, Bangalore 560 017, India

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Abstract

Measurement of solar cell parameters is important for the design of satellite power systems. These parameters can be measured using impedance spectroscopy and an equivalent circuit model developed. In this study parameters of a Back Surface Reflector Field solar cell (BSFR) have been measured using impedance spectroscopy. The results show high diffusion capacitance of BSFR cells and their exponential relation to the operating voltage. Cell dynamic resistance, diode factor, transition capacitance, and series resistance could also be measured. The minority carrier life time also has been calculated.

Keywords: Solar cells; BSFR cell; Impedance spectroscopy; Diffusion capacitance

1. Introduction

Impedance spectroscopy is the tool, generally employed by electrochemists to measure the kinetics of electrodes. However, this tool can be applied almost anywhere, and particularly to systems modelled by an equivalent circuit. From the equivalent circuit elements the physical or chemical parameters of the system can be calculated. This technique is particularly suitable if the equivalent circuit consists of one or two time constants, separated sufficiently or if one of them is dominant.

In this technique, the device is suitably biased for the DC conditions and a small AC signal, less than the thermal voltage (kT/e) or (RT/F) is superposed over the DC voltage. The impedance of the device is measured by measuring the in-phase and the quadrature components of the resulting current. The impedance is generally measured in the series equivalent form $R_s \pm jX_s$ over a wide range of frequencies, two to four decades, and from the argand plot of the impedance, the equivalent circuit components can be calculated.

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In this study impedance spectroscopy has been applied to measure the parameters of a solar cell. In a solar cell, generally, the AC equivalent circuit is neglected and only the DC equivalent circuits are used in the analysis of their interaction with the loads. With the introduction of new technologies, like the back surface field (BSF) and back surface field and reflector (BSFR) solar cells, the solar cell diffusion capacitance has increased substantially. When used with several cells connected in parallel and series to form solar panels, the increased capacitance has considerable effect on the design of the switching regulators used to regulate the voltage of the solar panels. Hence, it is essential to measure the capacitances associated with solar cell and other resistances at different conditions.

The AC equivalent circuit of a solar cell is shown in Fig. 1 [1] where

C_T = transition capacitance
C_d = diffusion capacitance
R_p = parallel resistance due to recombination in the transition region
R_d = the dynamic resistance of the cell
r = the series resistance due to bulk and interconnects
I_{sc} = the short-circuit current of the solar cell

Since, C_T and C_d are in parallel, this equivalent circuit has a single time constant equal to

$$T = \frac{R_d R_p}{R_d + R_p} (C_T + C_d). \tag{1}$$

Hence, the impedance spectrum of a solar cell (i.e., complex plot of R_s and X_s for a range of frequencies) should be a semicircle of diameter

$\frac{R_d R_p}{R_d + R_p}$, displaced from the origin by r.

When X_s is maximum,

$$X_s = \frac{R_d R_p}{R_d + R_p} = \frac{1}{2\pi f (C_T + C_d)}. \tag{2}$$

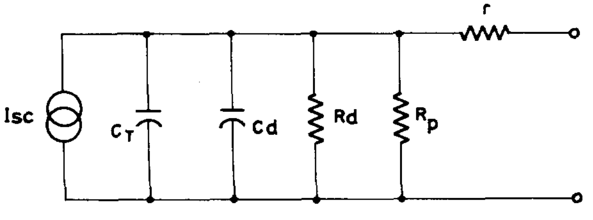

Fig. 1. AC equivalent circuit of a solar cell.

From this the value of $(C_T + C_d)$ can be calculated. Depending on the operating conditions, it may be possible to neglect R_p and C_T permitting calculation of C_d and R_d.

2. Experimental set up

In this study, the parameters of a 2 cm × 4 cm BSFR solar cell was measured at room temperature (22 to 24°C). The cell characteristics were measured in the dark by injecting current into the cell. The test setup consisted of a solartron electrochemical interface (ECI) together with the frequency response analyser (FRA) as shown in Fig. 2. The ECI acts as a potentiostat, holding the cell potential at the desired value. This also has provision for measuring the cell potential, current and an analog output port for interfacing with the FRA for impedance measurement. The FRA injects the required AC signal over the DC potential via. ECI and the resulting voltage and current are measured by FRA. The FRA calculates the impedance $(R_s + jX_s)$ of the cell and outputs the results, over a GPIB port.

The ECI and FRA provide several features to improve the accuracy of measurements. The ECI provides for attenuation of the input signal by 100 times to reduce the noise in the signal received by FRA. In order to improve measurement accuracy by FRA, ECI filters the DC component of the signal and amplifies the AC component by 10. The FRA makes impedance measurements over several periods of the input signal and outputs the value only if the average value of several measurements is within $\pm 1\%$. FRA measures the cell impedance over a range of frequencies automatically and sends the result over GPIB to a computer for storage. The setup used here can be easily automated through a computer.

In this study the excitation voltage selected was 10 mV as this is less than the thermal voltage kT/e ($\sim$ 26mV) at 22°C. This ensures minimum deviation from the DC conditions imposed. The impedances were measured in the frequency range 63.1 KHz to 10 Hz with ten steps per decade, distributed equally on a logarithmic scale to ensure evenly distributed measurement points. Measurements were made at 0.2, 0.3, 0.4, 0.45, 0.5, 0.55, 0.58, and 0.6 V in the forward direction, with the cell enclosed in a dark box.

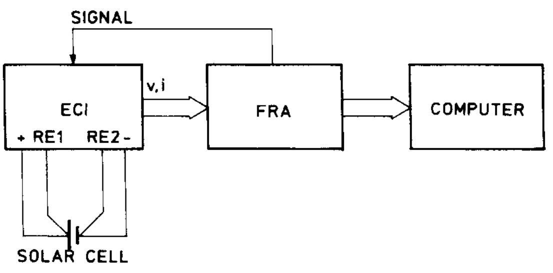

Fig. 2. Test setup for measuring solar cell impedance spectrum.

3. Results and discussions

The impedance spectrum (plot of $R_s \pm jX_s$ in the complex plane) of the BSFR solar cell is shown in Fig. 3 at 0.6, 0.5, 0.4, 0.3 and 0.2 V. Though measurements were made at other voltages only these five have been shown to illustrate the idea. It may be observed that these plots are very nearly semicircular in shape indicating that the AC equivalent circuit of the solar cell consists of an R and a C in parallel.

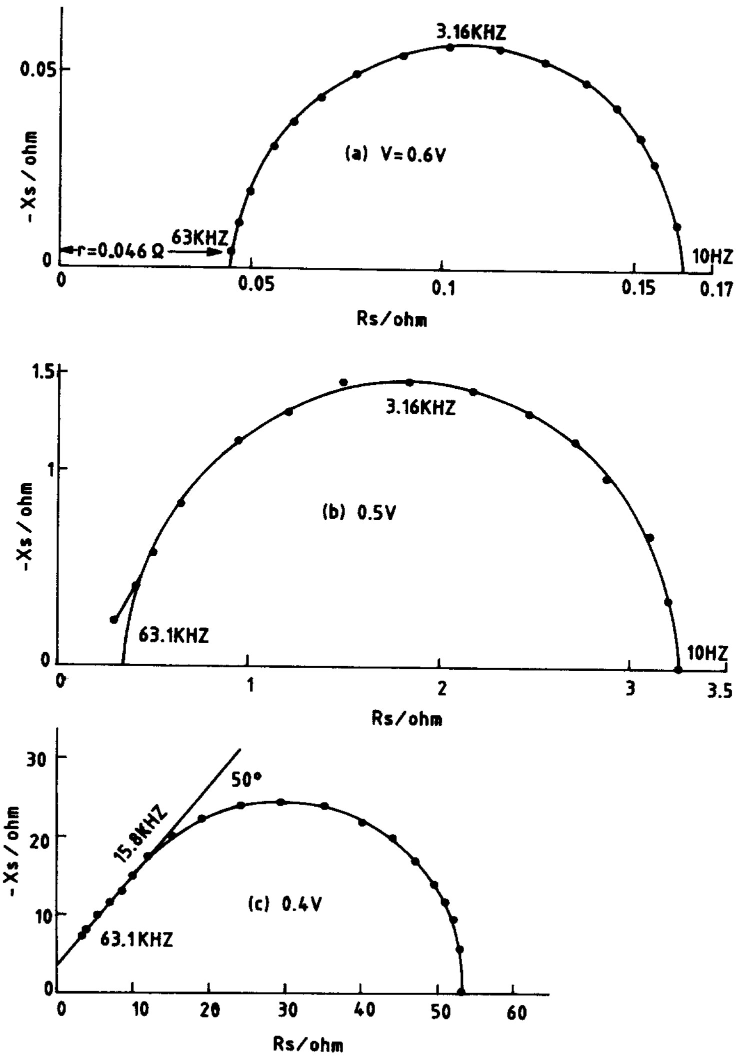

Fig. 3. Impedance spectrum of a 2cm*4cm BSFR solar cell at: (a) 0.6 V, (b) 0.55 V, (c) 0.5 V, (d) 0.4 V, (e) 0.3 V, and (f) 0.2 V.

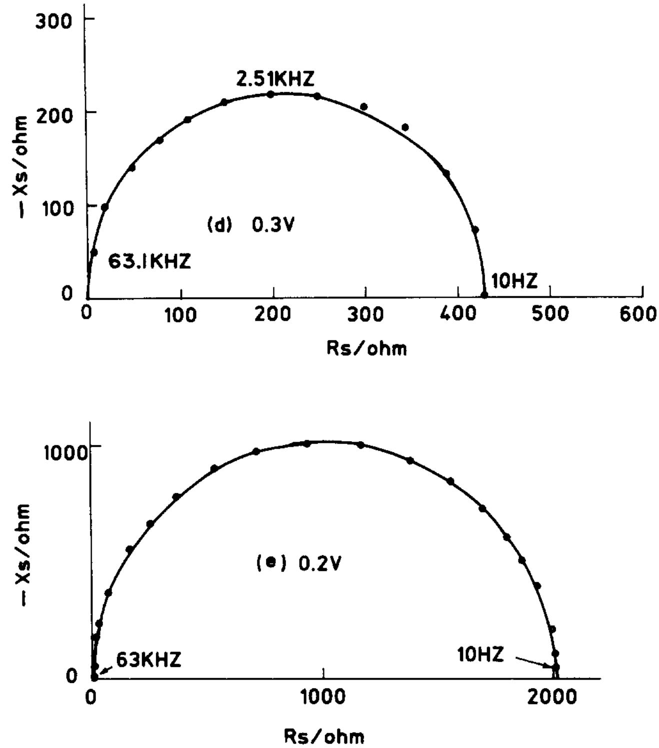

Fig. 3 (continued).

At 0.6 V the semicircle is shifted from the origin by 0.046 ohm. As indicated earlier this is equal to the series resistance of the solar cell. The diameter of the semicircle is 0.11 ohm which is equal to the dynamic resistance of the diode (R_d) as the parallel resistance R_p is very large and can be neglected. From the measured impedance $R_s - jX_s$ around the maximum of X_s, C_d, and R_d can be calculated by series to parallel transformation as below.

$$R_d = \frac{(R_s - r)^2 \pm X_s^2}{(R_s - r)}; \; x_d = \frac{(R_s - r)^2 + X_s^2}{X_s}, \tag{3}$$

$C_d = \dfrac{1}{2\pi f X_s}$, where f is the frequency of measurement.

It may be observed from Fig. 3 that the impedance spectrum is very close to a semicircle at low frequencies (< 3.1 KHz) and at higher frequencies it shows tendency to flatten out. This tendency increases as one goes from 0.6 V towards lower voltages and at 0.4 V, the spectrum is nearly a straight line at 50°. However, at 0.3 V and 0.2 V, the spectrum returns to near semi-circle shape at all frequencies.

In Table 1 the values of r, C_d, R_d are tabulated for different voltages as calculated from the measured spectrum. It may be observed that as the cell voltages decreases the

Table 1
Variation of solar cell parameters with cell voltage

Cell voltage (V)	r (ohm)	C_d (μF)	R_d (ohm)	$\tau(R_d C_d/2)$ (μs)
0.6	0.045	450	0.112	25.6
0.58	0.055	260	0.227	27.75
0.55	0.08	98	0.614	27.85
0.50	0.3	16.6	2.92	24.2
0.45	–	2.54	12.3	15.6
0.40	–	0.47	49.4	–
0.30	–	0.158	438	–
0.20	–	0.134	2018	–

accuracy with which r can be determined reduces and hence, have not been tabulated for voltage below 0.45 V.

The value of the diffusion capacitance C_d, defined as dQ/dV depends on the method of measurement and the waveform of the excitation signal [3]. For a sinusoidal input

$$C_d = \frac{\tau e}{2k\eta} I_o \exp(eV/\eta kT) \text{ for } W\tau \ll 1, \tag{4}$$

and

$$C_d = (\tau/2W)^{1/2} \frac{e}{k\eta} I_o \exp(eV/\eta kT) \text{ for } W\tau \gg 1, \tag{5}$$

where

e	= electronic charge
k	= Boltzmans constant
T	= temperature
η	= diode factor
τ	= minority carrier life time
W	= 2 π * frequency of applied signal

Under steady state condition for a step input ($t \to \infty$) the above value of C_d increases to

$$C_d = \frac{\tau e}{\eta k} I_o \exp(eV/\eta kT). \tag{6}$$

In the present study, the diffusion capacitance measured is C_d called the dynamic diffusion capacitance. It can also be shown that 2 C_d $R_d = \tau$ from the above equations, where R_d is the dynamic resistance of the solar cell, measured at frequency f such that $W\tau \ll 1$. At higher frequencies where $W\tau \gg 1$ the dynamic resistance R_d is also a function of frequency as below:

$$R_d = (2W/\tau)^{1/2} \frac{1}{eI_o} \exp - (eV/\eta kT). \tag{7}$$

It has been shown earlier that if the capacitance and the resistance are constant then, the impedance spectrum of such a circuit is a semicircle. If C and R vary with frequency as shown above (Eqs. (6) and (7)) then the impedance spectrum is a straight line with a slope of 45 degrees [2]. However, for a solar cell whose capacitance and dynamic resistance are constant at lower frequencies ($W\tau \ll 1$) and vary as root of W at higher frequencies ($W\tau \gg 1$), the impedance spectrum deviates from that of a semicircle tending towards a straight line at high frequencies [4].

If it is assumed that the value of τ is about 25 μs for a BSFR type solar cell then $W = 1$ at $f = 1/25 \times 10^{-6} \times 2 = 6.4$ KHz.

So, for frequencies below 6.4 KHz, C_d and R_d are constant with frequency, and for frequencies above 6.4 KHz, C_d and R_d vary with frequency. It may be observed from Fig. 3, that the peak of X_s occurs at 3.16 KHz or below and the impedance spectrum is fairly close to a semicircle up to about 15.8 KHz. Above this frequency, observable deviation from semi circularity is seen. At a cell voltage of 0.4 V the impedance spectrum is a straight line at 50 degrees up to about 15.8 KHz. At 0.3 V and 0.2 V the impedance spectrum returns to semicircular shape. This happens as the dominant capacitance at these voltages is the transition capacitance which is independent of frequency.

It may be observed that the diffusion capacitance C_d is exponentially related to cell voltage. Taking the logarithm of Eq. (6),

$$\log[C_d] = \log(1/2\,\tau e I_o/\eta k) + (e/2.3kT\eta)\,V. \tag{8}$$

Hence, the plot of log C_d must be linear with the cell voltage. Such a plot is shown in Fig. 4. Up to about 0.4 V log C_d is indeed linear with the cell voltage with a slope of 15.13 and a Y intercept of -0.374. The straight line was fitted by linear regression whose regression co-efficient was as high as 0.9995. From the slope of the straight line it is possible to calculate the diode factor which turns out to be 1.12 which is fairly close to unity. Below 0.4 V, the transition capacitance dominates and, hence, the relation deviates from a straight line.

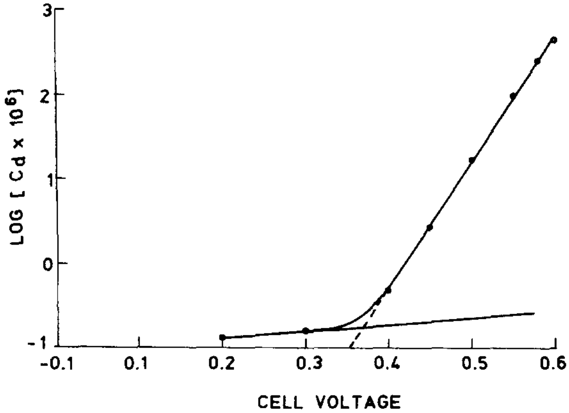

Fig. 4. Plot of log(C_d) versus the cell voltage.

It may be observed from Table 1 that τ appears to decrease at lower cell voltages: < 0.5 V. The equations derived above assume that the reverse leakage current is very small compared to the forward current. But at voltages below 0.5 V, the reverse leakage current is comparable to the forward current and τ is not equal to $2C_d R_d$.

The dynamic diode resistance (R_d) is also measured by impedance spectroscopy. This parameter is of importance for dynamic modelling of a solar array when used with a switching regulator. It may be observed that R_d tends to a value determined by the cell diode leakage current.

4. Conclusion

Impedance spectroscopy offers a simple method for measurement of diffusion capacitance in a solar cell. The experimental results on a BSFR solar cell show that the diffusion capacitance is large and is maximum at open-circuit voltage. The diffusion capacitance shows frequency dependence at very high frequencies ($W\tau \gg 1$). The impedance spectroscopy also measures the dynamic diode resistance whose value is essential for dynamic modelling of the photovoltaic power system and ensuring stability. Thus, parameters of a solar cell can be measured by impedance spectroscopy.

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