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Application of an impedance spectroscopy technique to study silicon solar cells and induced n^+-p-p^+ junction structures

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An impedance spectroscopy technique is applied to measure solar cell parameters under dark conditions. The impedance data have been used to calculate the series resistance, diode factor, minority carrier lifetime; cell dynamic resistance and transition capacitance. The values of first three parameters are compared with those measured by conventional methods, which were in close agreement with each other. The technique has also been applied to an induced n-p-p^+ structure (created by deposition of semitransparent Al and Pd layers on the two side of a p-Si wafer), developed to measure the lifetime in silicon, in order to understand the device structure, underlying physics and role of interfaces in determining the values of various parameters, particularly the lifetime values.

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1. Introduction

Solar cell panels are interfaced with their loads through an electronic power conditioner and a battery, in order to supply uninterrupted power to the load at the desired power rating. To design an efficient and reliable power conditioner, a thorough understanding of both the static (dc) and dynamic (ac) characteristics of the cell/panel is necessary. The static characteristics of solar cells are routinely measured and are indeed well understood, whereas the dynamic characteristics have not received much attention.

The impedance Spectroscopy Technique (IST) has been applied to systems modelled by an equivalent circuit from which the physical or chemical parameters of the system can be calculated. IST is particularly useful if the equivalent circuit consists of one or more time constants (two or more RC circuits), separated sufficiently, or if one of them dominates over the other. The impedance of the network is measured, and from this values of the circuit components can be calculated.

In the case of solar cells, the dynamic equivalent circuit is derived from a static equivalent circuit by replacing the diode with the junction, transition and diffusion capacitances, and its dynamic resistance. Using a spectroscopy technique, solar cell parameters such as the dynamic resistance, transition capacitance, diode factor, and series resistance can be determined; as well the value of minority carrier lifetime. It also provides an insight into the basic understanding of the device and the underlying physics. In the recent past, IST has been successfully employed to study crystalline silicon, amorphous silicon, and gallium arsenide, cadmium telluride and dye-sensitised solar cells [1-5].

In this paper, we report the application of the impedance spectroscopy technique to study (i) a crystalline silicon solar cell and (i) an induced junction (created by metals of different work functions on the two sides of the wafer) structure fabricated on p-type single-crystalline silicon wafers.

2. Principle

Impedance spectroscopy (a non-destructive and particularly sensitive to small changes in the system) technique involves the measurement and analysis of impedance related functions, where a small applied perturbation (i.e. ac signal), over a pre-determined frequency domain varying over several decades (two to four) and wherein the complex impedance Z (V/I = Z'+jZ") of a device, is measured directly. The complex plane plot, `Nyquist Plot' (i.e., Z' vs. Z") for varying frequency gives the impedance spectrum of the device. The impedance spectrum of a simple RC circuit consisting of a parallel resistor (R_p) and capacitor (C_p) is a semicircle in the fourth quadrant, with its origin at (Rp/2, 0) and a single time constant. If the semicircle is shifted from the origin (R_s+R_p/2, 0), this indicates the presence of series resistance (R_s) in the network. On the other hand, the impedance spectrum of double RC sub-circuits (two parallel resistors R_{p1}, R_{p2} and capacitors: C_{p1}, C_{p2}) in series with a resistor R_s, show two semicircles, the radius of which depends on the ratio of the two RC time constants τ_1 and τ_2. However, in practice, at times, a distorted semicircle is observed. If one of the two time constants dominates over the other, only one semicircle is visible in the Nyquist plots. The impedance spectrum of devices that consist of number of RC sub-circuits ($\tau_i = \sqrt{(R_iC_i)}$ where 'i' represents the number of RC circuits, i =1,2 ….n) may result in a highly distorted spectrum consisting of a number of semicircles that makes analysis complex and cumbersome. This is because, at times, it becomes difficult to separate the sub-circuits.

A single- or two-diode model, generally, models silicon solar cells. The equivalent ac-circuit is shown in [2], where it is assumed that the first of the two sub-circuits represents the junction and the second relates to the back contact.

3. Experimental details

The experimental set-up consists of a frequency response analyser (FRA, Solartron Model 1260A), a computer with the data acquisition and Z-plot software, an electrochemical interface (ECI), and the device under test (DUT). Two types of sample, a silicon solar cell and an induced n-p-p$^+$ junction structure developed to measure the lifetime in p-type silicon [6], have been used in the present study. The impedance spectroscopy measurement was carried out on a silicon solar cell whose performance parameters were known, in order to validate the system and also to cross check our results.

During impedance measurements, an ac signal with varying frequencies (1 Hz to 10 MHz) of amplitude less than the thermal voltage (to minimize the perturbation on the operating conditions) was superimposed across the sample, along with a dc bias voltage. The measurements were carried out in dark conditions, under forward and reverse bias conditions.

Thin semitransparent Al and Pd layers were deposited on either side of a <100> p-Si wafer (0.3-5 ohm cm resistivity, both sides highly polished, 350 μm thick and 50 cm diameter) by vacuum evaporation. Subsequently, no heat treatment was given to the samples. Inversion and accumulation layers are created on the two sides by the metal layers of different work function, i.e. Al (4.28 eV) and Pd (5.12 eV) respectively, resulting in an induced n-p-p$^+$ structure. For lifetime measurements, the photocurrent was measured as a function of the light intensity, using an 850 nm interference filter. The test structure was illuminated from the Pd side under two conditions; (i) in atmosphere ambience and (ii) under vacuum. It was noticed that the lifetime values fall as a function of storage time in an ambientatmosphere. However, this anomaly was not observed under vacuum [6] or in an inert atmosphere. The purpose of carrying out impedance spectroscopy on these samples was to get a better understanding of the device structure, the role of interfaces (i.e., Pd/Si and Al/Si) and also the role of the ambient conditions.

4. Results and discussion

It was observed that the impedance spectrum (in complex plane) is nearly semicircular in shape in the silicon cells (Fig. 1). This clearly indicates the predominance of a single time constant of an equivalent circuit consisting of single RC network. The shift along the positive real axis away from the origin near to the open circuit voltage is a measure of the series resistance of the cell.

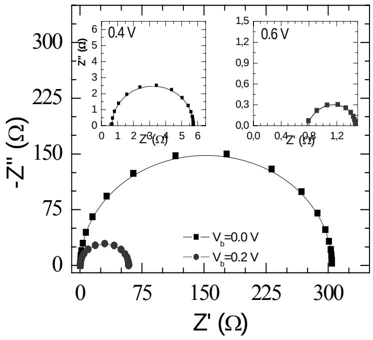

Fig. 1. Impedance spectra of a silicon solar cell for different forward biasing (V_b= 0 to 0.6 V). The two insets show Z' vs. Z'' curves for V_b 0.4 and 0.6 V (value close to the open circuit voltage of the cell). The curve for V_b= 0.5 is superimposed on the 0.6 curve). R_s and Rp values are 0.78 and 303 Ω respectively.

The open circuit voltage and short circuit current density of the solar cell were 0.690 mV and 24.8 mA/cm^2 respectively. The series resistance, diode factor and minority carrier lifetime; cell dynamic resistance and transition capacitance were determined, and the values of the first two parameters were compared with the values measured by conventional methods, which were in close agreement (±5%) with each other. The deviation from the semicircle at a bias voltage of +0.6 V in the high frequency regime (inset on the right in Fig. 1) may be attributed to variations of C_p and R_p with frequency, as reported earlier [2].

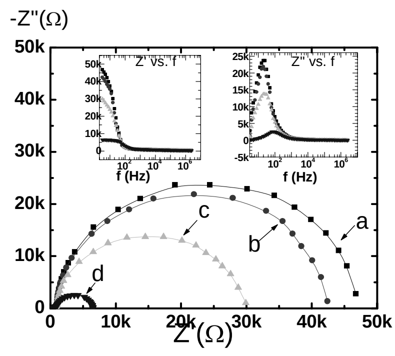

Fig. 2. Impedance spectra of a DUT at different reverse biases (V_b= 0.5, 0.3, 0.1 and 0V (curves a, b, c and d respectively). The two insets show Z' vs. f (left) and Z'' vs. f (right) curves for the above biasing, where the values decrease with the increasing reverse bias.

The Nyquist plots for the test structure having an induced n-p-p$^+$ junction on a single crystalline silicon wafer (referred as DUT in the subsequent text) are shown in Figs. 2 and 3 for forward and reverse bias respectively.

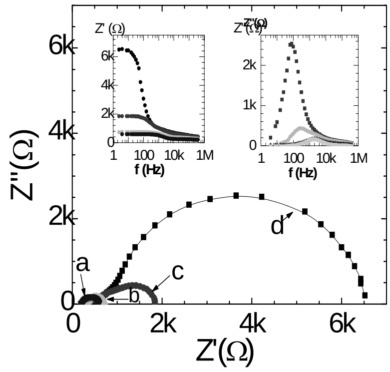

Fig. 3. Impedance spectra of a DUT at different forward biasing (V_b= 0.5, 0.3, 0.1 and 0V (curves a, b, c and d respectively) under vacuum. The two insets shows Z' vs. f (left) and Z'' vs. f (right) curves for the above biasing where the values decreases with the increase

Fig. 2 shows the impedance spectrum of the test structure at 0.5, 0.3, 0.1 and 0 V under reverse bias conditions in vacuum. The responses for all biasing conditions are characterized by semicircles (centre displaced below the real axis at an angle ranging between 6-10°) indicating a single AC equivalent circuit of the structure, consisting of R and C connected, in parallel with a single time constant. However, the radii of the semicircles vary with bias voltage and decrease with decreasing negative bias (minimum at zero bias).

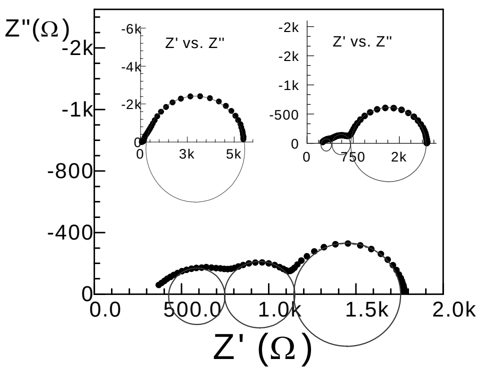

Fig. 4. Impedance spectra of a DUT at zero bias. The inset on the left shows the Z' vs. Z'' curve under vacuum, whereas the curve on the left is just after breaking the vacuum. The main curve depicts the "Nyquist Plot" after long exposure of the DUT under atmospheric ambience.

On the other hand, an opposite behaviour is observed in the case of forward bias (Fig. 3) where the radius of semicircles decreases with the increasing positive biasing and is a maximum at zero bias, with a highly deformed semicircular shape (Fig. 3b and 3c) in the high frequency regime. This distortion could be due to a second RC-component adding to the original RC circuit (single). The shift in the frequency with bias can be seen from the Z" vs. f (frequency) curves plotted in the insets of Figs. 2 and 3.

In induced junctions such as the DUT, the bias conditions change the widths of the accumulation and depletion layers. It is expected that at a certain value of V_b, the depletion layer may collapse completely and the device may cease to work (as a p-n junction). It is known that the impedance spectra are predominantly governed by the bulk properties of the material in the low frequency regime, and once the frequency is increased the contributions from the back contact, low-high junction of solar cells, interfaces etc become more pronounced.

It has already been mentioned that the characteristics of the induced n-p-p+ structure depend strongly on the ambient conditions, which has been reflected in the lifetime values in our earlier studies [6]. To observe the effect of atmosphere ambience, the vacuum was released and impedance measurements were carried out immediately and again after leaving the specimen in room ambience for several hours. This is shown in the impedance spectra in Fig. 4.

The inset in the left side of Fig. 4 depicts that Nyquist plot (Z' vs. Z'') for the DUT under vacuum, where the single loop (that fits well to a semicircle equation) indicates the presence of a single RC circuit. However, the centre of the circle is displaced below the real axis at an angle ~7°.

The inset in the right of the same figure shows the Z' vs. Z'' curve when the measurement was done just after breaking the vacuum. Here, distortion in the semicircle at the high frequency side (i.e. the left), is visible. The observed curve seems to be composed of three semicircles that may be separated from each other as shown in the figure or may be inter-mingled. The main figure (Fig. 4) shows the spectroscopic data taken after the exposure of the specimen in ambient for several hours. It is evident that the dimensions of the sub-semicircles on the left have increased considerably, which may be attributed to the added contributions owing to the additional RC sub-circuits introduced into the original circuit due the change in interfacial properties while exposing the DUT to the ambient. It is to be noted that sub-semicircles may appear on either side of the main semicircle. For example, additional sub-circles are observed in the case of multi-crystalline materials at lower frequencies.

We believe that the properties of the aluminum or palladium layers, or both, are affected by the ambient (due to adsorption or absorption of oxygen, moisture etc.), influencing the interfacial properties (either the Al/Si or Pd/Si interface, or both) of the induced n-p-p+ junction structure. Consequently, anomalous lifetime values were observed with storage time and conditions.

4. Conclusions

The impedance spectroscopy technique has been applied to an induced n-p-p+ junction structure (created by semitransparent Al and Pd layers on either side of p-Si wafer), developed to measure the lifetime in p-type silicon, in order to understand the device structure, the underlying physics and the role of interfaces in vacuum and atmospheric ambient. It was found the interfacial properties (either Pd/Si or Al/Si, or both) are influenced in ambience, resulting in anomalous lifetime values. Impedance spectroscopy measurements were also carried out on a crystalline silicon solar cell, and parameters such as the series resistance, diode factor and minority carrier lifetime have been determined from complex plane plots and compared with the values measured by other techniques, which were in agreement (±5%).

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