Electrical Impedance Spectroscopy (EIS) for Photovoltaic Materials: Possibilities and Challenges

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Abstract. Electrical Impedance Spectroscopy (EIS) is a noninvasive material characterization technique which provides the frequency response of the electrical impedance of materials under test as the signature of the material properties. EIS injects constant amplitude AC electrical currents and measures the developed potentials at different frequency points to calculate the complex electrical impedance. In EIS, the electrical impedance profile of a material is correlated with its structure and composition for material testing either online or offline. EIS is found as a fast, portable, user-friendly, and noninvasive technique and hence, it has been utilized for material characterization in a number of engineering fields and applied science areas. In the past few decades, EIS has also been used to characterize the photovoltaic materials. This paper reviews the possibilities and challenges of EIS technique applied for the characterization of the photovoltaic materials. The paper presents a brief discussion about the EIS technology, applications of EIS on PV materials along with the advantages and limitations of the technology. The paper concludes with the highlight of the recent trends of EIS based PV material characterization process mentioning the challenges of the technique.

1. Introduction

Electrical Impedance Spectroscopy (EIS) [1-4] is an electrical impedance-based nondestructive testing (NDT) [5] technique that is used for noninvasive characterization of materials. For a material under test, the EIS studies the frequency response of the complex electrical impedance to characterize the object in terms of its impedance and phase angle. In EIS, a constant amplitude alternating electrical current signal is applied at many frequency points and the developed potential data are measured at all the frequencies using an array of surface electrodes [6-7]. The current injection and the voltage measurement both are noninvasively conducted using the surface electrodes connected with dedicated instrumentation capable of constant amplitude current injection at a number of frequency points and simultaneous voltage measurement. In EIS, the information on the anatomy/structure, and composition of materials can be studied [4] in terms of their electrical impedance profile obtained in a wide frequency range and the information can be utilized for online or offline material characterization. Being a fast, user-friendly, and noninvasive technique the EIS has been utilized for material characterization in chemical and material engineering [8-9], mechanical engineering [10], civil
engineering [11], biomedical and biotechnological engineering [12-13], food technology [14-15] and other fields of engineering and technology [16]. As a noninvasive and nondestructive material characterization technique, the EIS has also been applied in the photovoltaic (PV) technology [17-18] for photovoltaic materials and device characterization. Photovoltaic materials are the materials which are used to develop PV-cells or solar cells [19]. As photovoltaic systems [20] have been proven itself as a promising technology for green energy harvesting [21], a remarkable demand in PV-cell manufacturing is found in recent days. As shown in the Fig. 1, a PV system consists of a PV panel, connected with a controller circuit, battery (storage unit) and an inverter. PV panels (Fig. 1) are developed with PV modules (Fig. 1) developed with PV-cells. As the PV-systems has lower power conversion efficiency (PCE) compared to conventional energy generation systems, the PV-cell manufacturers are always looking for better PV-cell development using either the new PV-materials [22-23] or a new fabrication process [24] or both to achieve higher efficiency at a lower cost. In this paper, the possibilities and challenges of the EIS technique applied for the characterization of photovoltaic materials have been review and presented. The paper discusses the EIS technology, applications of EIS on PV materials along with the advantages and limitations of the technology. The paper also discussed the recent trends of EIS based PV material characterization highlighting the challenges of the method.

![Figure 1. Electrical power generation from sunlight through solar cell panel developed with PV-modules which contain many photovoltaic (PV) cells.](image)

2. Materials and Methods

2.1. Electrical Impedance Spectroscopy (EIS)

EIS is a noninvasive impedance measurement technique in which the complex electrical impedance of any object ($Z_o$) and its phase angle ($\theta_o$) is measured at a number of frequencies ($f_n$) [7]. To measure the $Z_o$ and $\theta_o$, an AC current signal with constant amplitude is injected to the object and the voltage developed due to that current signal is measured. The measurement is repeated at different frequencies and the $Z_o$ and $\theta_o$ obtained at all the frequency points are collected. The measurement of the voltage data generated due to the current injection is conducted through either two electrode method [7] or four electrode method [7]. The voltage data are divided by the current data to get the amplitude of $Z_o$ and $\theta_o$. The real part ($R_o$) of $Z_o$ and the imaginary part of $Z_o$ ($X_o$) are also calculated from the impedance amplitude ($|Z_o|$) and phase angle ($\theta_o$). The Nyquist plot [7] is obtained from the real part ($R_o$) and imaginary part ($X_o$) of the impedance ($Z_o$) by plotting $X_o$ over $R_o$ and the plot is utilized for deriving the equivalent circuit model of the object.

2.2. EIS for Material Characterization

Every material has its own electrical impedance which varies with frequency if there any capacitive reactance ($X_C$) or inductive reactance ($X_L$) are found in its composition and structure [7] because $X_C$
and $X_c$ both are frequency dependent. If the structure and/or composition are changed the electrical impedance will be also varied [7]. Therefore, the complex electrical impedance ($Z_e$) can be found as a signature or information of many properties of the material being studied. Therefore, by studying the profile of the electrical impedance ($Z_e$) of a material over a particular frequency band, one can probe its properties in terms of the electrical impedance which can be utilized for material characterization. Photovoltaic materials can also be studied by EIS and the PV-cell properties and a number of cell parameters can be obtained from the impedance data. As, the EIS process investigates the electrical impedance at different frequencies, the frequency response of the PV materials, PV-cell and junction properties all can be derived from the impedance response of the PV-cells. Hence, carefully analyzing the impedance response and the equivalent circuit models the design parameters and the cell properties can be understood in detail and also can be modified them for better cell fabrications.

2.3. Photovoltaic (PV) Cells

A (PV) cell or solar cell can directly convert solar energy into electrical energy [17-19] and hence it is utilized to harvest electrical energy from sunlight. The process by which a PV-cell generates electricity is called the photovoltaic effect which was first demonstrated in 1839 by Edmond Becquerel. PV-cells are developed with two different types of semiconductors: a P-type semiconductor material and an N-type semiconductor material which are joined together to create a P-N junction and hence PV-cell is basically found as a PN junction device [25]. According to the photovoltaic effect, when light is fallen to a semiconductor material, the photons of the absorbed light provides sufficient energy to the electrons to move through the junction creating an electric current flow through the material [17-19]. A silicon solar cell (single junction) can produce approximately 0.5 to 0.6 volts as the maximum open-circuit voltage [26]. As the electricity generated by a single solar cell is very low in amplitude, many cells are connected together in series-parallel combinations to increase the voltage and current levels. The combinations of many solar cells to generate larger amount of power is called PV modules and the PV modules are connected to form the PV panels. The efficiency of a PV-cell, which is defined as the ratio of the amount of electrical power generated by a PV cell to the incidental energy coming from sunlight, is generally low [27]. The efficiency of a PV-cell depends on the quality of the radiation (sunlight intensity and wavelengths), temperature [28], solar cell design and properties [29-30] as well as some other factors [27]. Depending on the material used and other design parameters the efficiency of the PV-cells is determined.

Solar cells may be of different types such as crystalline silicon cells (monocrystalline and polycrystalline) [31], thinfilm solar-cells [32] and organic solar-cells [33]. Monocrystalline solar cells are developed from a single crystal of the silicon whereas melting together many molten shards of silicon crystals is used develop polycrystalline cells. Thinfilm solar cells are developed with thin layers or films (few microns thick) of specific materials deposited on a glass, plastic or other substrates. Organic solar cells are developed with the organic materials or polymers rather than semiconducting materials. Though an organic solar cell has a lower efficiency and a shorter lifetime but is found as a low-cost device.

2.4. PV-Cell Materials and Structure

A PV-cell (Fig. 2) is developed with N-type and P-type material along with an antireflection layer on the top (above N-type layer) and a flat electrical conducting layer at the back (below the above P-type layer). The lower most electrical conducting layer acts as the positive electrode whereas the negative electrodes are fabricated with electrically conducting material on the N-type layer. An antireflection layer is also deposited on the N-type layer to increase the absorption of the light energy. A glass protective layer is put on the antireflection layer to enhance the mechanical strength of the structure and to protect all the other layers. The negative-electrodes on the top of the N-type material are developed with a few finer (thin) electrically conducting materials to avoid the obstruction to the sunlight entering to the PV-cell. As soon as the solar cell is exposed to the sunlight, the light passes
through the glass layer and the antireflection layer and reaches the P-N junction. When the light reaches the junction of the P-type and N-type layers called P-N junction, the photons presented in the light energy creates a number of electron-hole pairs which can flow through the junction and can create an electrical current if the electrodes are connected with a conductor or load making the circuit closed. In this way the light energy is converted into the electrical energy which is known as photovoltaic effect.

![Solar Cell Diagram](image)

**Figure 2.** The construction of a solar cell showing the different layers, P-N junction and the energy conversion in p-n junction.

### 2.5. EIS of PV-Cells and Equivalent Circuit Modeling

The PV-cell basically forms a P-N junction consisting a depletion layer between P-type material and N-type material. The static equivalent circuit of the cell [34-36] is found as an electrical circuit comprising a current source ($I_{ph}$), one diode (D), and two resistors called shunt resistor ($R_{sh}$) and series resistor ($R_s$). $I_L$, $I_D$, and the resistors $R_{sh}$ are connected parallel and the resistor $R_s$ is connected series with this parallel branch. The current $I_L$ represents the current generated by the light photons inside the cell, $I_D$ represents the current lost to recombination, whereas the current lost due to shunt resistances is represented by $I_{sh}$. The resistance $R_{sh}$ (shunt resistance) is considered as the resistance of the alternate paths of the leakage current conduction through a PV-cell. The resistance $R_s$ (series resistance) exhibited from the energetic barriers at interfaces and bulk resistances within layers. $R_s$ is responsible for the losses occurred due to the interconnection and cell solder bonds, junction box, etc. [34] whereas the $R_{sh}$ responsible for the leakage currents contributed by the high conductivity shunts created across the junction (P-N junction) of the cell [34].

The DC (static) and AC (dynamic) characteristics of the PV-cells are essential to be understood in detail for designing these power conditioners [37-38]. For a solar cell, though the static voltage-current characteristics are well understood [34-36, 39-40], but, the dynamic characteristics (AC characteristics) still require to be studied more [37]. The static and dynamic equivalent circuits of a PV-cell are shown in Fig. 3 and 4 respectively [38]. The AC equivalent circuit of a PV-cell could be obtained from a static equivalent circuit by replacing the diode with its junction capacitances and its dynamic resistance ($R_d$) [38]. The transition capacitance represented by $C_t$ and the diffusion capacitance denoted by $C_d$ are found as the junction capacitances of PV-cells [38].

The PV-cells have their own electrical properties depending on the materials use, structure of the cell, and other manufacturing parameters. Therefore, the PV-cells will have its distinguished electrical properties which can be probed to characterize the PV-cells. The EIS can be applied to monitor the frequency response of the PV-cells and can be characterized noninvasively. A number of research groups studied the EIS to characterize different PV-cells and PV systems. A brief summary of few of the studies on the applicability of the EIS technique for PV materials has been presented below.
Figure 3. Static (DC) equivalent circuit of a solar cell showing the different components and current through it.

Figure 4. Dynamic (AC) equivalent circuit of a solar cell which represents the different components and current through it.

3. EIS Based PV-Cell Characterization

The EIS has been applied to study the PV-cell material and their characterization. The following sections will present a few of the research works where the EIS has been utilized for studying PV-Cells, its materials and fabrication parameters to improve the cell design and development with better power conversion efficiency.

Kumar et al., 2000 [37] studied the AC parameters of silicon PV-cells and gallium arsenide (GaAs/Ge) PV-cells using EIS studies and investigated about their cell capacitance [37], dynamic resistance [37] and series resistance [37]. Two types of solar cells viz: BSR (back surface reflector) silicon solar cells and the BSFR (Back Surface Field and Reflector) silicon solar cells are studied. In space technology the BSR and BSFR-silicon PV-cells are used as the major types of PV sources [37]. The application of GaAs/Ge PV-cells in space is also increasing because GaAs/Ge not only provides high efficiency [37] and large radiation resistance [37] but also it provides high temperature
application [37] facility. BSR silicon solar and BSFR silicon solar cells have 10% to 14% efficiency and whereas the GaAs/Ge have the efficiency of around 20% [37]. Authors reported that the BSR and BSFR silicon solar cells showed transition as well as diffusion capacitance. But throughout the operating range, the GaAs/Ge PV-cell showed only the transition capacitance.

Kumar et al., 2001 [38] studied the AC impedance of BSR silicon solar cell using EIS utilizing an experimental setup developed. The frequency response analyzer was used to excite the solar-cell to measure the ac parameters using the EIS technique. Authors applied a pure sinusoidal signal of an amplitude of 10 mV (r.m.s.) to the solar cell samples biased with a DC voltage of 1V and studied the impedance response between a frequency range of 1 Hz to 60 kHz distributing the frequency points on a log scale with 10 points per decades.

Kumar et al., 2005 [41] studied the impedance response of BSFR silicon PV-cell at different temperature using EIS because the temperature of the solar panel placed in any application in the space varies from 190° to 375° K [41]. Authors reported that, generally, in space the operating voltage of a PV-array is fixed and, as the temperature of the PV-array changes, the point of operation (V-I) of the array is shifted [42]. Therefore, in a PV system in space, if a PV panel gets a partial shadow on it, the PV-cells under the shadowed region are reverse biased by the PV-cells which are still illuminated [43-44]. The authors conducted impedance spectroscopy study on BSFR silicon PV-cells to understand the variation of the AC parameters of silicon PV-cell at different temperatures both at forward and reverse biased conditions. The temperature of the BSFR silicon solar cells is varied from 190°–375° K and the AC parameters of the PV-cells are measured to create a database which would be an important information which could be suitably utilized in the design of solar-power systems.

Proskuryakov et al., 2009 [45] fabricated the electrical properties of CdTe/CdS solar cells with metal organic chemical vapor deposition (MOCVD) using various chemical concentration and structural and studied their impedance properties using electrical impedance spectroscopy under varied intensity of illumination. CdTe/CdS cells were fabricated by MOCVD with variations in structure and doping and a generalized impedance model was developed to apply to the cells developed. The intensity of the illumination is varied from 1 to 10–4 sun [45] and the information on the PV-cell properties are studied where 1 sun [46-47] represents a standard illumination at AM1.5, or 1 kW/m² [46-48]. Authors not only investigated the properties of the P-N junction of the cells under light, but also they studied the minority carrier lifetime and the back contact. They also studied the effect of resistive ZnO layer which has been integrated between the transparent conductor layer and the CdS layers in few PV-cell samples. The results obtained from the PV-cells with different concentrations of As, demonstrated that at lower As-concentrations, the total device impedance as well as the series resistance (R_s) both are increased and consequently the collection current and efficiency are reduced. At the lowest value of As-concentrations, the lifetime of the minority carrier was found to be larger compared to the optimized devices. Authors reported that the incorporation of the resistive layer of ZnO did not affect the device impedance and R_s under 1 sun illumination whereas at lower light intensities a significant contribution of ZnO layer on the R_s and R_s was observed. Authors also mentioned that the higher CdTe:As doping at the back contact dramatically reduced the total impedance (Z_t) and R_s. Measurements of the cell impedance in the dark are conducted with the cells at different DC bias and the data were compared to the results obtained at illuminated conditions. Author suggested that, for polycrystalline thin-film PV-cells, the EIS measurements on the PV-cells in the light (in the open circuit condition) are found as the preferred experimental techniques for PV-cell characterization and equivalent circuit modeling.

Sarker et al. 2017 [49] studied the application EIS on dye-sensitized solar cells (DSSCs) with different electrode geometries and analyzed the electrochemical impedance spectra to characterize the DSSCs solar cells. The authors investigated the effect of the electrode geometries on DSSCs by analyzing
their impedance profiles obtained from the EIS measurement as well as the voltage-current (V-I) plots. The impedance analysis showed a strong correlation between the magnitude of series resistance ($R_s$) of the DSSCs PV-cells and their photovoltaic performances. The authors reported that the Ohmic resistance ($R_o$) not only depends on the active area geometry of the cells but also on the substrate resistance (sheet resistance) although the $R_s$ is not significantly found affected by the other series resistive elements. Therefore, the substrate sheet resistance should be as small as possible because, in a cell $R_o$ is the main part of the $R_s$. Author mentioned that their analysis demonstrated that for a smaller active area the photovoltaic performance is found better. Authors reported that for a given active area of a DSSC PV-cell, large $S_{AW}$ and small $S_{AL}$ were found as the keys to achieve the maximum efficiency [49]. $S_{AL}$ and $S_{AW}$ are the dimensions of the mesoporous films of nanocrystalline TiO$_2$ which was deposited with a thickness (average thickness) of 8 μm on the cleaned FTO (Fluorine doped Tin Oxide) substrates. Authors claimed that their study would help to develop the large modules of DSSCs based PV-cells without compromising with the photovoltaic performance of the cells.

Mullenbach et al., 2014 [50] applied EIS for studying the bulk heterojunction (BHJ) organic photovoltaic cells (OPVCs) in The authors also conducted the reverse bias external quantum efficiency measurements to extract of the recombination rate constant (RRC) and transit rate constants (TRC). The transit and recombination rate constants are studied for OPVCs with different electron donor-acceptor pairings and compositions and demonstrated that a large RRC can be accompanied by a large TRC. Author reported that the fast recombination is not necessarily harmful to the performance of the OPVCs. They mentioned that the extracting the RRC and TRC one can not only understand the basis of optimum OPVCs device configurations but also understand how the transient behavior of charge carriers is influenced by the OPV architecture and processing conditions.

Garcia-Belmonte et al., 2008 [51] used the electrical impedance spectroscopy (EIS) to study the impedance properties of an absorber blend developed for bulk heterojunction (BHJ) organic solar cells. The authors studied the charge carrier diffusion and recombination in the cells and presented the directly measured data for the capacitance under reverse-voltages and forward-voltages of a BHJ structure developed with the composition of ITO/PEDOT:PSS/P3HT:PCBM/Al. The absorber blend was developed with P3HT (poly (3-hexylthiophene)) and PCBM ([6,6]-phenyl C61-butyric acid methyl ester) along with ITO (indium tin oxide) and Al (aluminum) contacts and conducted the analysis on the charge carrier diffusion and charge carrier recombination in the dark. Authors reported that Mott–Schottky-like behavior was exhibited by the reverse bias capacitance which indicates the formation of a Schottky junction at the contact of P3H:PCBM-Al. Authors noticed that the capacitive response obtained at forward bias is found as an important as it indicates about the electrons (minority carriers) play a significant role. EIS measurements demonstrated that electrons (minority carriers) were diffused out from the depletion zone of the P3HT:PCBM-Al and at the forward bias the capacitive response is evoked due to the accumulation. Using the EIS data and the impedance modeling obtained from the spectroscopic study, both the recombination time of the electrons (minority carriers) as well as the mobility of the electrons (minority carriers) at forward bias in the dark are extracted. Authors claimed that utilizing EIS studies and impedance data the mobility and the effective lifetime of the electrons (minority carriers) can easily be obtained to understand the doped BHJ devices and their inner mechanisms in detail.

Quantum dot solar cells (QDSCs) [52] are the PV-cells which are developed with the quantum dots which can be developed with adjustable bandgaps by varying the size of the dots. Wang et al. [53] applied EIS to study the CQD-SCs and to probe their recombination-resistance, carrier-lifetime, capacitance, and electrical conductivity. Authors developed two PbS-CQD solar cells viz: Au/PbS-TBAI/ZnO/ITO and Au/PbS-EDT/PbS-TBAI/ZnO/ITO and studied the impedance parameters of PV-cells developed using EIS [53]. They reported that the insertion of the PbS-EDT layer greatly enhanced the recombination-resistance, carrier-lifetime, capacitance, and electrical conductivity.
compared to the cells without PbS-EDT layer [53]. The investigators mentioned that their experimental studies can help to better understand the physical mechanism beneath for CQD-SCs which is essential for fabricating the CQD-SCs with higher (PCE).

Sharma et al., 2020 [54], investigated the commercially available polycrystalline silicon solar cell using EIS under different conditions which can degrade the PV-cell performance. The mechanical stress, hotspot, and disconnection of interconnection ribbon are created for PV-cell samples and the cells are studied by EIS, Fourier transform and I-V characteristic. Authors reported that the EIS study can be effectively utilized to monitor the degradation of the PV-cells as the results obtained from the EIS showed that the parallel resistance (R_p) decreases from 283.60 to 234.80 Ω, from 273.0 to 187.10 Ω and from 352.80 to 345.20 Ω for the mechanical stress test, the hotspot and the disconnection of interconnection ribbon test respectively.

4. Advantages and Limitations of EIS
EIS is a frequency domain technique in which electrical impedance of an object is measured to characterize it. Electrical impedance data measurement is conducted with surface electrodes preferably with four electrode method. EIS is found as fast noninvasive low cost technique which potentially probes the PV-cell parameters to study and improve the design. EIS equivalent circuit modeling also helps us to understand the physics of the PV-cell and PV junction. Several PV-cell parameters are correlated with the impedance response of the cell and hence the design fabrication process could be modified to enhance the performance of the PV-cell. Connecting the PV-cell with the impedance analyzer or EIS instruments is a crucial as the dimension of the PV-cell is small in most of the cases and hence implementing the electrode connection if found difficult. Also, 2-probe method applied for the measurement process may cause error in measurement. The current amplitude also be selected carefully to limit the power disipation within the sample to ensure the application of the impedance measurement process without damaging the tiny PV-cell sample.

5. Discussion and Conclusions
Impedance spectroscopy is found a powerful tool for noninvasive material characterization and hence it has widely been applied to study the PV-cells and their design parameters utilizing the impedance responses. Various PV-cells have been studied with EIS and it is observed that the EIS can potentially be applied for crystalline silicon PV-cells, thin-film PV-cells, organic PV-cells, quantum-dot PV-cells etc. PV-cell parameters such as transition capacitance (C_t) and diffusion capacitance (C_d), dynamic resistance (R_d) and series resistance (R_s), parallel resistance (R_p) etc. are measured. The performance of PV-cells and photovoltaic phenomena can also be studied and correlated with the impedance data obtained in EIS. EIS measurement also can help us to study the transit and recombination rate constants for PV-cells. EIS based PV-cell characterization processes can help us to understand the physical mechanism of solar cells in detail which is essential for fabricating PV-cells with higher power conversion efficiency (PCE). Therefore EIS is found as a promising characterization technique which can be noninvasively applied for studying the PV-cell performance and associated PV-cell parameters.

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7. Conflict of Interest
The author hereby confirms that there is no con Conflict of Interest for this research work.

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