BEYOND STEADY-STATE CHARACTERISTICS: IMPEDANCE SPECTROSCOPY (A USEFUL TOOL FOR EXTRACTING SOLAR CELL PARAMETERS)

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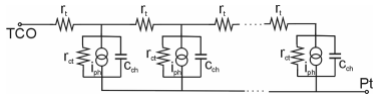
Optoelectronic Devices

Beyond *I-V* curves, impedance measurements consist of producing a small electric perturbation of the steady state in the organic- or dye sensitized solar cells. Such a technique is specially addressed to investigate dynamical processes (transport and recombination) which are expected to occur. Since the cell performance (power conversion efficiency) is in part limited by these effects, relevant information can be extracted from impedance measurements under variation of bias potential and light intensity.

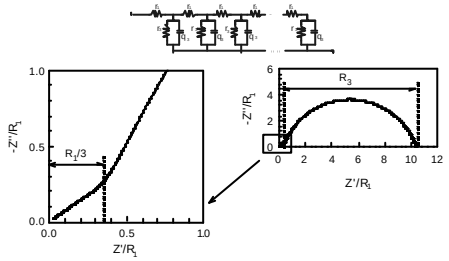
The group of Optoelectronic Devices at Universitat Jaume I began research activities in 1995. Our general topics of interest are materials, devices and nanotechnologies. More specifically, the group is specialized in modelling and analyzing the impedance response of dye-sensitized nanostructured TiO_2 films and polymer photovoltaic devices. We show here two examples of our recent research on these subjects.

Equivalent circuit for a generic heterogeneous photovoltage converter



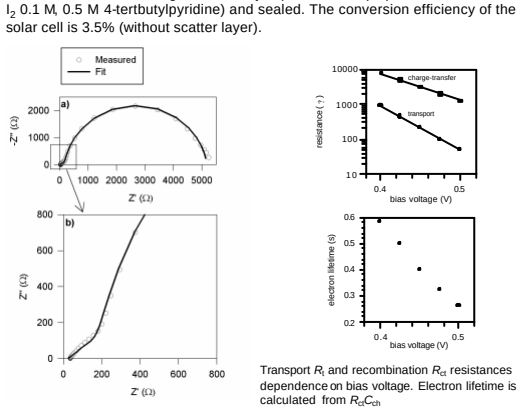
EC for a heterogeneous PV converter such as a DSSC. The transverse elements represent the three main processes occurring in the solar cell: A photocurrent generator stands for excitation of the absorber from ground to high energy level; the chemical capacitance accounts for the change of Fermi levels; the resistance indicates the recombination events from the phase of high to the phase of low pseudo-Fermi level. The upper line shows a diffusion resistance along the selective contact to the high-energy state, and the lower line represents the resistanceless (ideal) selective contact from the low energy state to the electrode.

Modeling: equivalent circuit simulations for solar cell response



Measuring + Parameter Extraction: Example *a*) Dye solar cell in the dark at forward bias

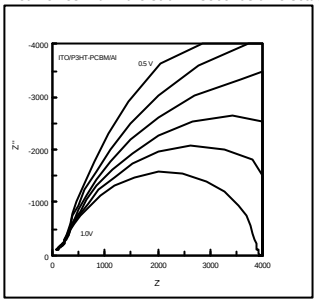
We show impedance measurements of a DSSC in the dark. The results reported here were obtained with a DSSC in the standard sandwich-type configuration in which a dyed nanoporous TiO_2 electrode is facing a Pt counter electrode. A 4 mm film of nanostructured TiO_2 was deposited over the substrate and sensitized with a Ru-complex dye. A platinized F:SnO_2 sheet was used as a counterelectrode. The cell was filled with organic electrolyte (acetonitrile, (Bu) 4NI 0.6M, LiI 0.1 M, I_2 0.1 M, 0.5 M 4-tertbutylpyridine) and sealed. The conversion efficiency of the solar cell is 3.5% (without scatter layer).



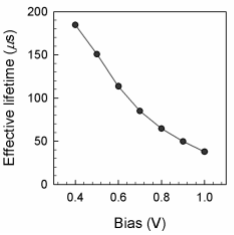
Transport R_t and recombination R_{ct} resistances dependence on bias voltage. Electron lifetime is calculated from $R_{ct}C_{ch}$

Measuring + Parameter Extraction: Example *b*) Bulk heterojunction P3HT/PCBM solar cell in the dark at forward bias

We have analyzed the charge carrier effective lifetime in bulk heterojunction solar cells of structure ITO/PEDOT/P3HT-PCBM/Al, by means of impedance spectroscopy analysis. Effective lifetime lies within the submilliseconds time scale.



Impedance spectra corresponding to bulk heterojunction solar cells in the dark at different forward bias.



Effective charge carrier lifetime extracted from the recombination response in the dark at forward bias.

More information (recent papers on impedance modeling and measurements):

1. F. Fabregat-Santiago, J. Bisquert, E. Palomares, L. Otero, D. Kuang, S. M. Zakeeruddin, M. Grätzel **Correlation between photovoltaic performance and impedance spectroscopy of dye sensitized solar cells based on ionic liquids** *Journal of Physical Chemistry C* , 111, 6550-6560 (2007).
2. I. Mora-Seró, Y. Luo, G. Garcia-Belmonte, J. Bisquert, D. Muñoz, C. Voz, J. Puigdollers and R. Alcubilla **Recombination rates in heterojunction silicon solar cells analyzed by impedance spectroscopy at forward bias and under illumination** *Solar Energy Materials and Solar Cells* , in press (2007).
3. Q. Wang, S. Ito, M. Grätzel, , F. Fabregat-Santiago, I. Mora-Seró, J. Bisquert, T. Bossho, and H. Imai **Characteristics of High Efficiency Dye-sensitized Solar Cells** *Journal of Physical Chemistry B*, **110**, 19406-19411 (2006).
4. I. Mora-Seró, J. Bisquert, F. Fabregat-Santiago, G. Garcia-Belmonte, Zoppi, G.; Durose, K.; Proskuryakov, Y.; Oja, I.; Belaidi, A.; Dittrich, T.; Tena-Zaera, R.; Katty, A.; Levy-Clement, C.; Barrioz, V.; Irvine, S. J. C. **Implications of the negative capacitance observed at forward bias in nanocomposite and polycrystalline solar cells** *Nano Letters,* **6**, 640-650 (2006).
5. J. García-Cañadas, F. Fabregat-Santiago, H. Bolink, E. Palomares, G. Garcia-Belmonte, J. Bisquert **Determination of Electron and Hole Energy Levels in Mesoporous Nanocrystalline TiO2 Solid-State Dye Solar Cell** *Synthetic Metals*, **156**, 944-948 (2006).
6. F. Fabregat-Santiago, J. Bisquert, E. Palomares, J. R. Durrant **Impedance spectroscopy study of dye-sensitized solar cells with undoped spiro-OMeTAD as hole conductor** *Journal of Applied Physics*, **100**, 034510 (2006).
7. G. García-Belmonte, J. García-Cañadas, I. Mora-Seró, J. Bisquert, C. Voz, J. Puigdollers and R. Alcubilla **Effect of buffer layer on minority carrier lifetime and series resistance of bifacial heterojunction silicon solar cells analyzed by impedance spectroscopy** *Thin Solid Films,* **514**, 254-257 (2006).
8. F. Fabregat-Santiago, J. Bisquert, G. Garcia-Belmonte, G. Boschloo, A. Hagfeldt **Impedance spectroscopy study of the influence of electrolyte conditions parameters of transport and recombination in dye-sensitized solar cells** *Solar Energy Materials and Solar Cells,* **87**, 117-131 (2005).
9. F. Fabregat-Santiago, J. García-Cañadas, E. Palomares, J. N. Clifford, S. A. Haque, J. R. Durrant, G. Garcia-Belmonte, J. Bisquert **The origin of slow electron recombination processes in dye-sensitized solar cells with alumina barrier coatings** *Journal of Applied Physics,* **96**, 6903-6907 (2004)**.**
10. J. Bisquert, A. Zaban, M. Greenshtein, I. Mora-Seró **Determination of rate constants for charge transfer and the distribution emiconductor and electrolyte electronic energy levels in dye-sensitized solar cells by open-circuit photovoltage decay method** *Journal of the American Chemical Society,* **126**, 13550 (2004).
11. J. Bisquert, D. Cahen, G. Hodes, S. Rühle, A. Zaban **Physical chemical principles of photovoltaic conversion with nanoparticulate, mesoporous dye-sensitized solar cells** *Journal of Physical Chemistry B,* **108**, 8106-8118 (2004).
12. A. Pitarch, G. Garcia-Belmonte, I. Mora-Seró, J. Bisquert **Electrochemical impedance spectra for the complete equivalent circuit of diffusion and reaction under steady-state recombination current** *Physical Chemistry Chemical Physics*, **6**, 2983-2988 (2004).
13. G. Garcia-Belmonte, J. Bisquert and G. S. Popkirov. ***In situ*** **electronic conductivity measurement in polybithiophene films using electrochemical impedance at different doping levels.** *Applied Physics Letters* , **83**, 2178-2180 (2003).