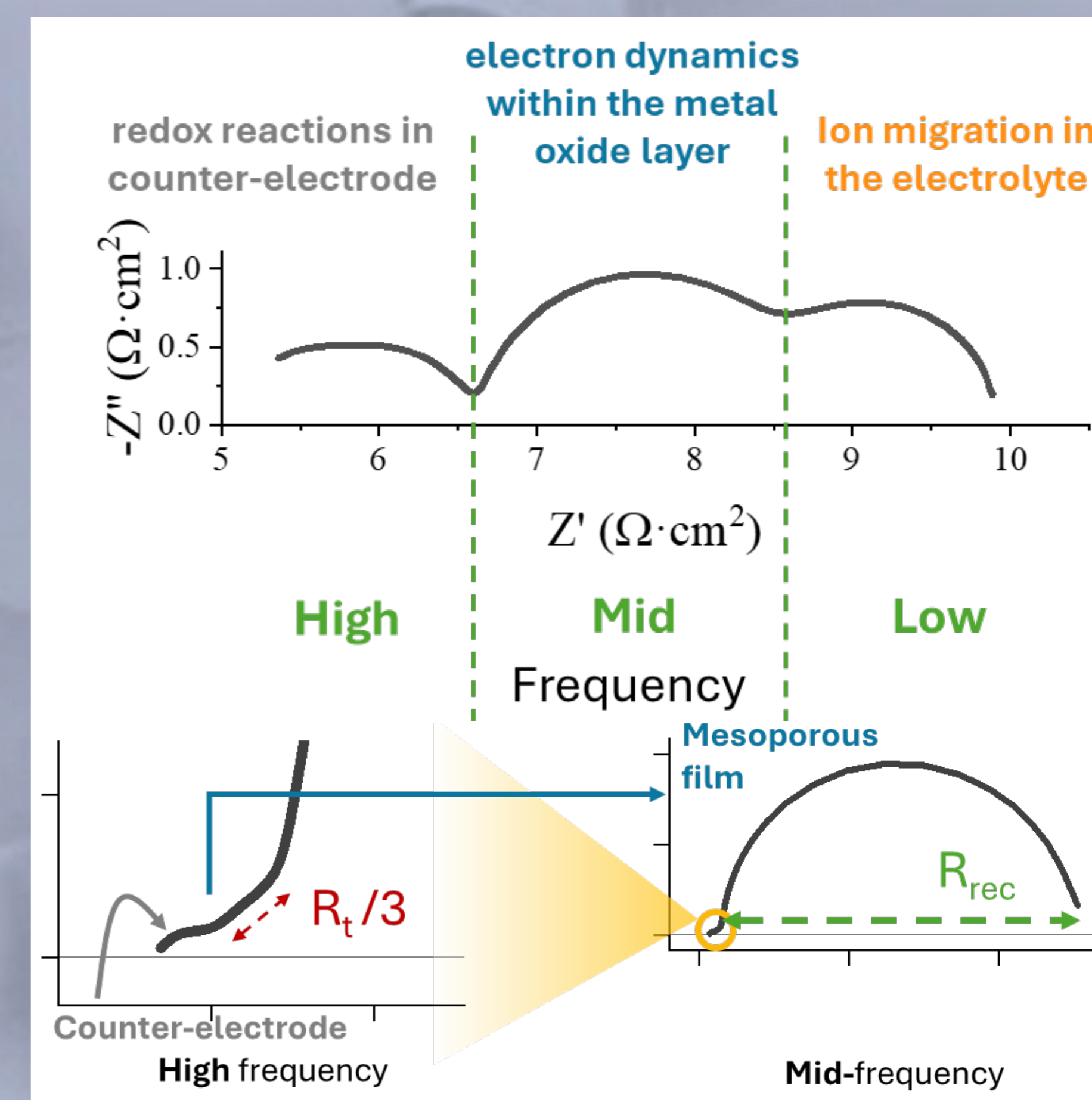
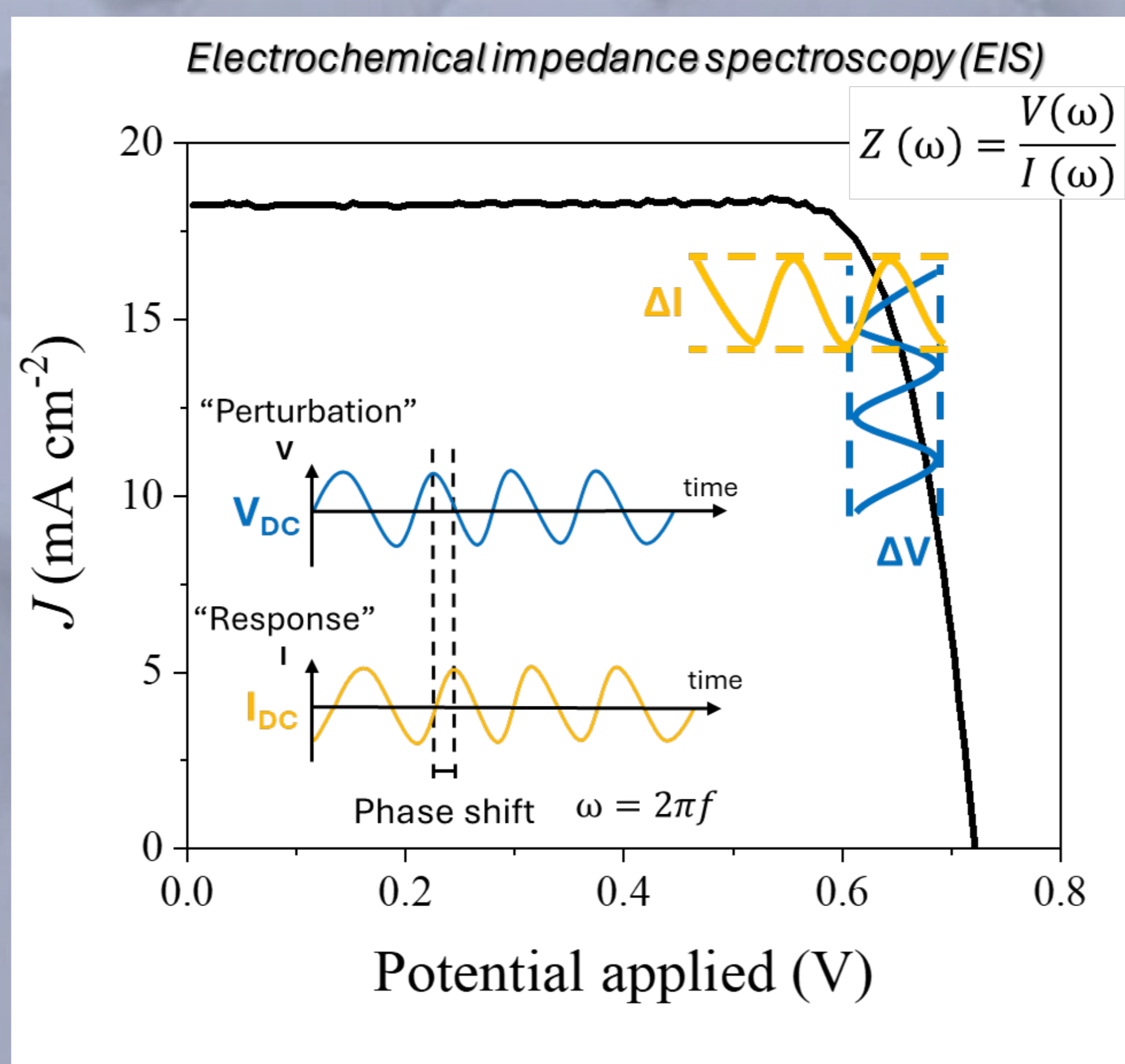
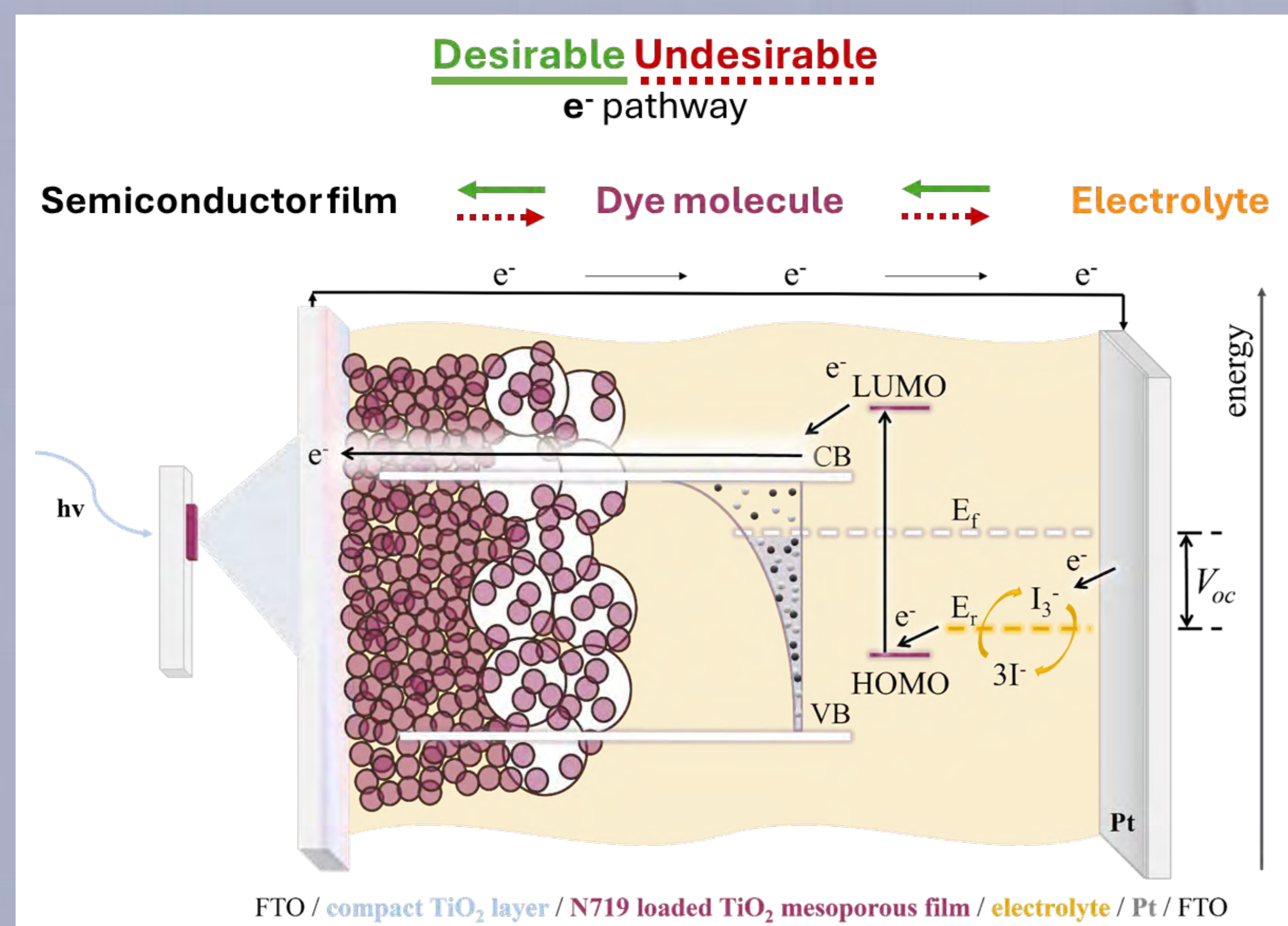


Design and Characterisation of Dye-Sensitised Solar Cells for Indoor Applications

Patricia Sánchez-Fernández, Gerko Oskam
 psanfer2@upo.es // gosk@upo.es



Competition between transport and recombination in DSC at Low light intensity

Patricia Sánchez-Fernández¹, Clara A. Aranda¹, Renán Escalante¹, Antonio J. Riquelme², Renaud Demadrille², Paul Pistor¹, Gerko Oskam¹, and Juan A. Anta^{1*}
¹Center for Nanoscience and Sustainable Technologies (CNATS), Department of Physical, Chemical, and Natural Systems, Universidad Pablo de Olavide, 41013 Sevilla, Spain | ²Grenoble INP, IRIG, SyMMES, CEA-Univ. Grenoble Alpes-CNRS, 38000 Grenoble, France

Impact of the TCO in the performance of DSC for Indoor Applications

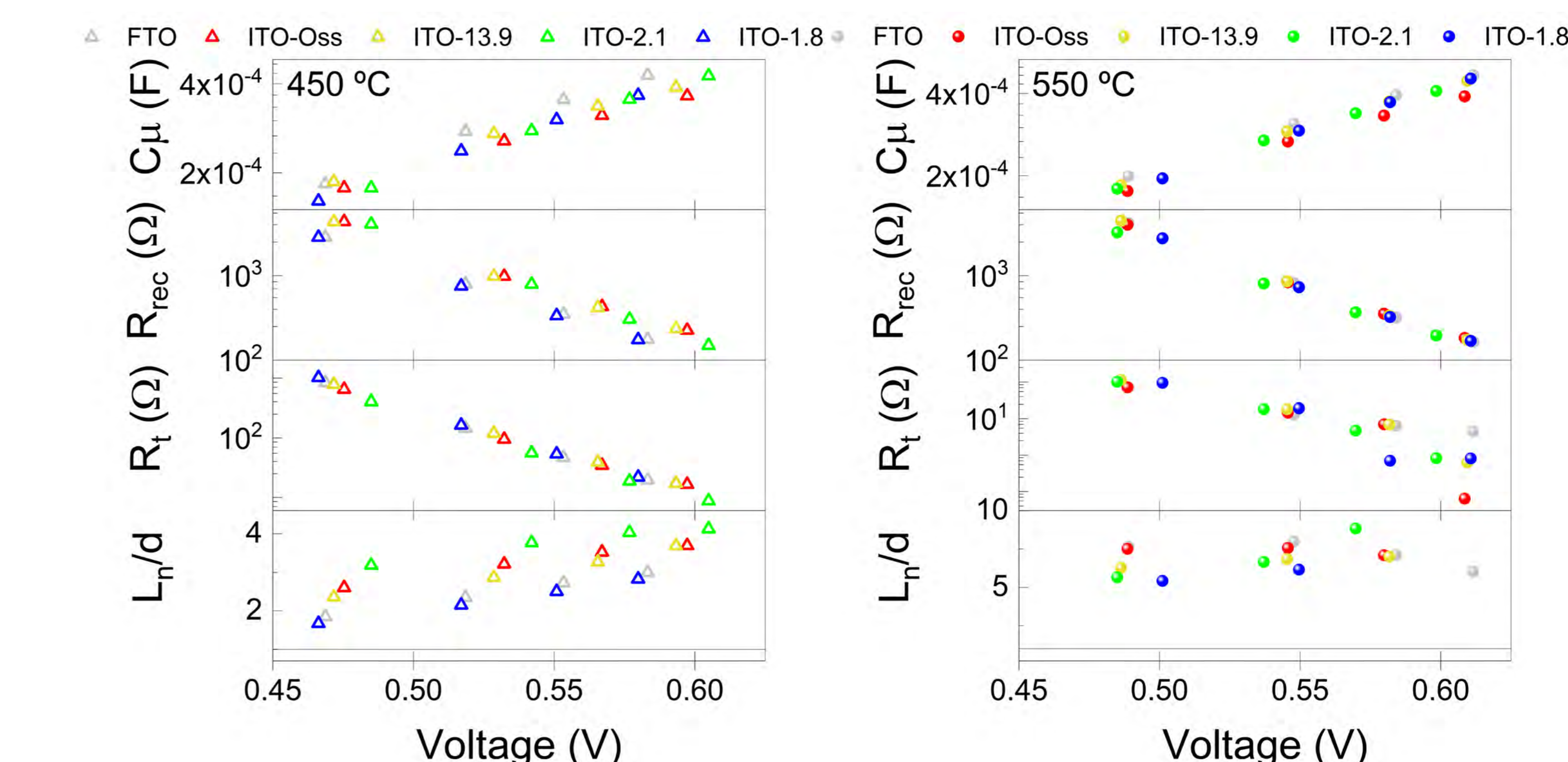
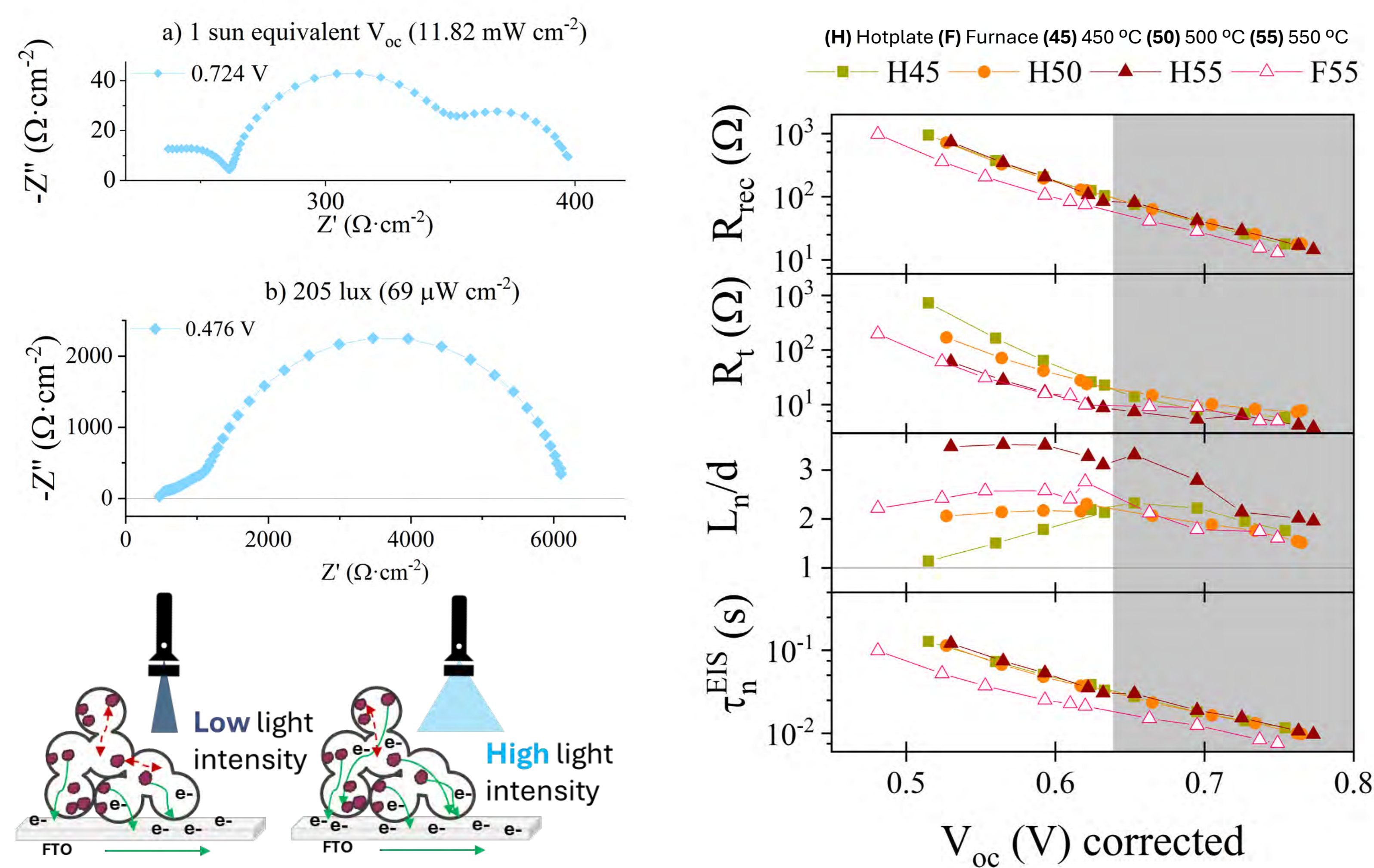
Patricia Sánchez-Fernández¹, Valid Mwalukuku¹, Marta Miró-Llorente², Renán Escalante¹, Pedro Vidal-Fuentes², Maxim Guć², Paul Pistor¹, Gerko Oskam¹, Clara A. Aranda¹, Juan A. Anta^{1*}
¹Center for Nanoscience and Sustainable Technologies (CNATS), Department of Physical, Chemical, and Natural Systems, Universidad Pablo de Olavide, Sevilla, Spain | ²Catalonia Institute for Energy Research (IREC), Barcelona, Spain

ABSTRACT

The efficiency of electron collection in a dye-sensitized solar cell (DSC) is determined by a delicate balance between **electronic transport and recombination losses** caused by electron transfer to dye cations and electron acceptors. While state-of-the-art DSCs have demonstrated quantitative electron collection under standard 1 sun conditions, the nonlinear nature of the trapping/detrapping dynamics in the photoanode with respect to the stored electronic charge can result in suboptimal performance under the low illumination intensity conditions commonly found indoors. Herein, the **key factors influencing electron collection in relation to light intensity** using impedance spectroscopy and numerical analysis are thoroughly examined. **Impedance analysis reveals that the electron diffusion length tends to decrease as the quasi-Fermi level is lowered, approaching the critical limit ($L_n/d \approx 1$) at intensities characteristic of indoor illumination.** A range of tert-butyl pyridine concentrations and different thermal and chemical treatments of the TiO₂ are tested, showing that this low intensity limitation is inherent to the multiple-trapping mechanism that governs the functioning of a DSC. It is concluded that relatively high ideality factors, nonoptimal electrolyte compositions, or small variations in the quality of the TiO₂ layer can result in electron collection limitations that are not apparent under 1 sun but become noticeable at low light intensities.

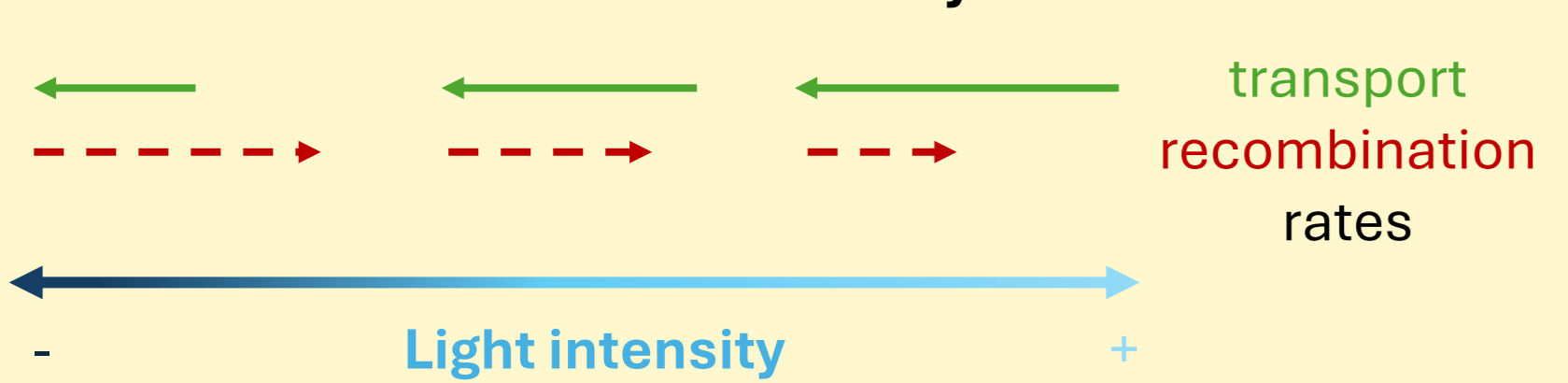
ABSTRACT

Improving the performance of dye-sensitized solar cells (DSC) under artificial light sources and at low light intensities requires preserving the adequate electron transport properties in the sensitised photoanode that are characteristic of DSC operation at 1 sun. Besides, parasitic resistance and optical losses must be reduced. In this respect, the impact of the chemical and electrical properties of the transparent conducting oxide (TCO) has somehow been overlooked. Considering the systematic reduction of the electron diffusion length as the low quasi-Fermi level regime is approached, subtle variations of the properties of the TiO₂ photoanode and its interaction with the TCO substrate can compromise optimal performance under indoor illumination. In this work, the performance of DSCs fabricated with commercial fluorine-doped tin oxide (FTO) and indium tin oxide (ITO) substrates, as well as newly prepared ITO substrates of varying conductivity, has been analysed. Furthermore, a variation of the preparation conditions for the TiO₂-based photoanodes was conducted, with thermal treatments at two different annealing temperatures (450 and 550°C). Photovoltaic characterisation and analysis of the impedance response reveal a low conductivity of the substrate proves to be only adverse under 1 sun illumination, deteriorating the fill factor due to the series resistance voltage drop. In contrast, under low illumination intensity, all studied substrates show comparable performance, which can be attributed to the negligible voltage drop over the series resistance related to the significantly lower photocurrent. As a consequence, **the conductivity of the TCO substrate is less critical when selecting a substrate for indoor applications.** However, **the choice of TCO affects the quality of TiO₂ photoanodes**, leading to shorter diffusion lengths in some cases. **Interestingly, the annealing temperature plays a critical role in homogenising the differences observed while also enhancing the diffusion length, ensuring efficient electron collection under low light conditions.**



CONCLUSION

Electron collection efficiency



At low energy levels, $L_n \approx d$
 • Non-quantitative collection efficiency occurs when the light intensity is sufficiently low.
Non-linear variation of the L_n/d with light intensity
 • State-of-the-art DSCs at 1 sun may mask **recombination losses** at low illumination levels.

This paradox suggests that even **slight modifications** to the metal oxide preparations and electrolyte compositions must be considered in the optimisation of DSC for indoor applications to **push efficiencies close to the thermodynamic limits for artificial light sources.**

Small perturbation techniques such as EIS and IMPS are specially suited to investigate **transport as a function of light intensity.**

CONCLUSION

- The choice and quality of the TCO can strongly affect the electronic properties and overall performance of DSCs, **especially under 1 sun illumination conditions.**
- Our results show that, under low-light intensities typical in **indoor environments**, while higher annealing temperatures improve electron transport and device performance, studying the effect of the **TCO is crucial for devices that require low-temperature processing of the TiO₂ mesoporous layer**, where performance can otherwise be limited.
- These findings underline the need to optimise both the TCO and processing conditions to achieve efficient DSCs for indoor use.

Small-perturbation techniques such as EIS serve as a key technique **providing fundamental insights** into the electronic processes governing device performance and **guiding optimisation efforts.**

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