Direct Observation of Surface Polarization at Hybrid Perovskite/Au Interfaces by Dark Transient Experiments

Jorge Caram\textsuperscript{1,2,3}, Marisé García-Batlle\textsuperscript{1}, Osbel Almora\textsuperscript{1,4,5}, Roberto D. Arce\textsuperscript{2,3}, Antonio Guerrero\textsuperscript{1}, and Germà Garcia-Belmonte\textsuperscript{1,*}

\textsuperscript{1} Institute of Advanced Materials (INAM), Universitat Jaume I, 12006 Castelló, Spain
\textsuperscript{2} Instituto de Física del Litoral (IFIS-CONICET), Güemes 3450 - 3000 Santa Fe, Argentina
\textsuperscript{3} Facultad de Ingeniería Química, UNL, Sgo. del Estero 2829 – 3000 Santa Fe, Argentina
\textsuperscript{4} Institute of Materials for Electronics and Energy Technology (i-MEET), Friedrich-Alexander-Universität Erlangen-Nürnberg, 91058 Erlangen, Germany
\textsuperscript{5} Erlangen Graduate School in Advanced Optical Technologies (SAOT), Friedrich-Alexander-Universität Erlangen-Nürnberg, 91052 Erlangen, Germany

*Email: garciag@uji.es

Abstract

A distinctive feature of hybrid perovskite light-absorbing materials is the non-negligible ionic conductivity influencing photovoltaic performance and stability. Moving ions or vacancies can naturally accumulate at the outer interfaces (electrode polarization) upon biasing. Contrary to that approach, a modulation of conductive or recombination properties could manifest as an alteration in the low-frequency part of the impedance response, either producing inductive or large capacitive features. Under this last view, capacitances are not the response of polarized structures or charging mechanisms, but result from the modulation of currents. This work intends to provide evidences that assist us in distinguishing between these two dissimilar mechanisms, namely, real charge polarization and delayed current effects under bias in the dark. The analysis relays upon an experimental technique based on transient charging signals using the Sawyer-Tower circuit. Instead of applying an alternating small perturbation over a steady-state voltage (differential capacitance method), transient charging measures the resulting polarization upon large bias step under suppression of dc currents. Our findings reveal that real steady-state charge is indeed induced by the applied voltage in the dark, easily interpreted by means of charged real capacitors with
values much larger than the film geometrical capacitance. The connection between that polarization and the charging of perovskite/contact interfaces is highlighted.
In just a few years, perovskite solar cells (PSCs) have gained great attention in the field of photovoltaics with an unprecedented increase in power conversion efficiency (PCE) achieved from facile solution processing routes.\textsuperscript{1-4} Despite those technological progresses, it was identified from the very beginning that slow responses in PSCs cause annoying deviations from common photovoltaic operation. The presence of slow relaxation processes (from milliseconds to minutes) yield different hysteretic $I - V$ curves depending on the bias sweep direction, scan rate, illumination and poling history.\textsuperscript{2,5-7} That phenomenon was initially connected to the observation of an excess capacitive signal in the low frequency part of the capacitance spectra,\textsuperscript{8,9} in relation to the polarization of the outer contacts upon bias which originates the so-called dark hysteresis. Reinforcing the idea of the interfacial charging under solar cell operation, several studies identified the formation of built-in potentials in the vicinity of the interface between the perovskite absorber and extracting layers.\textsuperscript{10} Using frequency-modulation Kelvin probe force microscopy (FM-KPFM), it has been identified that the electrical field in solar cells under working conditions mainly drops at the corresponding selective interfaces by local charge accumulation.\textsuperscript{11} A related phenomenon is the remnant open-circuit voltage commonly exhibited in long-time photovoltage decay experiments,\textsuperscript{12} which has been also explained in terms of the piling up of stabilized interfacial charge.

A distinctive feature of perovskite light-absorbing materials is the non-negligible ionic conductivity that is believed to influence photovoltaic operation.\textsuperscript{13,14} Moving ions or vacancies naturally accumulate at the outer interfaces (electrode polarization) upon biasing,\textsuperscript{15,16} originating the usually reported excess dark capacitance of order 1-10 $\mu$F cm$^{-2}$.\textsuperscript{9} Similarly to the accumulation of ionic species, interfacial electronic pileup has been proposed in order to interpret the commonly-reported light-enhanced capacitance at low frequencies.\textsuperscript{17} Accordingly, recent models can be found on the interplay of electronic carrier recombination and moving ion dynamics.\textsuperscript{18,19}

Previous works\textsuperscript{20} suggested a close dependence between the ionic environment and the recombination mechanism in PSCs, in such a way that ionic vacancies move to decrease the recombination flux. It has been also argued\textsuperscript{21} that such a coupling effect between ionic and electronic charges has an influence at low frequencies, as carrier recombination current becomes phase-delayed with respect to the voltage perturbation. Under this view, low-frequency light-enhanced capacitance is caused by out-of-phase carrier recombination instead of charge accumulation currents. Sophisticated equivalent circuits (ionically-gated transistor interface) have been proposed\textsuperscript{22} accounting for the ionic-electronic interplay governing charge injection and recombination. Similar arguments have appeared very recently but now disregarding ionic effects and highlighting delayed electronic injection currents as the sole cause of the low-frequency capacitive phenomena even in the dark.\textsuperscript{23} These kind of models are specially rich as introduce a modulation of conductive or recombination properties that ultimately manifests as an alteration in the low-frequency part of the impedance response.\textsuperscript{24} Their
use are well-known in Electronics. For example, the conductivity modulation of \( p-n \) junction diodes at forward bias produces inductive loops,\(^{25}\) or the thermal diffusivity of thermoelectric models give rise to large low-frequency capacitances.\(^{26}\)

As a consequence, it is still under debate whether large capacitive effects observed at low-frequencies in PSCs are exclusively explained from charge accumulation mechanisms (interface polarization) or a dynamic interplay between ionic kinetics and electronic carrier recombination/injection current is occurring giving rise to apparent (not real) capacitors. Our work intends to provide evidences that assist us in distinguishing between real charge polarization and delayed current effects under bias stimuli in the dark. This distinction is crucial for understanding PSCs basic functioning and device operation.

We select here perovskite films of methylammonium lead iodide (MAPbI\(_3\)) as active layer, symmetrically contacted by interdigitated gold electrodes (see below for experimental conditions). This experimental setup allows avoiding the formation of a photovoltage under light irradiation, expected when asymmetrical (different work function) materials are used as selective contacting layers. One can observe in Fig. 1 the impedance and capacitance responses registered at zero-bias in the dark and ambient conditions, exhibiting two main features: at high- and intermediate-frequencies (\( f > 100 \) Hz) the geometrical capacitance \( C_g \approx 2.7 \, \text{pF} \) and sample resistance dominate; and at low-frequencies the commonly reported excess capacitance increment \( C_s \gg C_g \) is observed. The same electrical response is observed for 1 V-bias (Fig. S1) and corresponds to the equivalent circuit of Fig. S2. An estimation of the effective polarization area of the interdigitated electrodes is included as Supplemental Information, which results in values of the geometrical capacitance per unit area of \( C_g \approx 0.1 \, \text{nF cm}^{-2} \).
FIG. 1 a) Example of impedance plot and b) capacitance spectrum response of a 320 nm-thick MAPbI$_3$ film, measured at zero bias in the dark, exhibiting the low-frequency capacitive features. In both graphs, red lines represent a fitting with the corresponding equivalent circuit (Fig. S2).

Because small-amplitude capacitive analysis by itself is not able to unambiguously discern if the low-frequency capacitance is effectively caused by charge polarization, we propose here to relay upon a different experimental technique based on transient charging signals. Instead of applying an alternating small perturbation over a steady-state voltage (differential capacitance method), transient charging measures the resulting polarization upon large bias step under suppression of dc currents. The experimental setup is based on the Sawyer-Tower circuit (ST) which is the classical set-up used to explore hysteretic loops of ferroelectric materials. The configuration of the circuit is shown in Fig. 2(a). A step voltage signal (V$_{app}$) is applied to the sample $C_x$ across a reference linear capacitor $C_0$, with both capacitors in series connection. The condition $C_0 \gg C_x$ must be accomplish to assure that the applied voltage principally drops within the perovskite sample. Under this condition the charge storage in $C_x$ (as in $C_0$) is $Q = C_0 V_0$, being $V_0$ the voltage at the reference capacitor ([see Fig. 2(b)], which is recorded with an ultrahigh input resistance (1 TΩ) potentiostat to avoid loading effects from the recording instrument. The total transfer function of the measuring set-up is given in SI.

As observed in Fig. 2b, the voltage at $C_0$ follows the bias perturbation steps in such a way that only a small portion drops at it, i.e. $V_0 \ll V_{app}$. Note that this fact discards the observation of the reference capacitor $C_0$ charging through the perovskite sample shunt resistance, which would yield $V_0 = V_{app}$ in the long time (see more discussion below). To verify the effective perovskite film effect on the reported polarization, the set-up response comprising only gold electrodes on glass substrates were checked (see Fig. S3). Since the reference capacitor suppresses any dc current, a registered steady-state voltage after long-enough poling should correspond to the effect of a true charging mechanism. Otherwise the reference capacitor cannot withstand a constant polarization. A delayed or modulated injection current is not able to yield a permanent voltage on the reference capacitor plate. On the contrary, a measured potential at $C_0$ should indicate a kind of locally imbalance charges at the perovskite sample.

All materials were used in our experiments as received: CH$_3$NH$_3$I (DYESOL), PbI$_2$ (TCI, 99.99%), N, N-dimethylformamide anhydrous (Sigma Aldrich, 99.8 %), dimethylsulfoxide anhydrous (Sigma Aldrich, ≥ 99.9 %), and chlorobenzene anhydrous (Sigma Aldrich, 99.8 %). The perovskite precursor solution is obtained from reacting dimethylformamide (DMF) solutions (50 wt. %) containing MAI and PbI$_2$ (1:1 mol %) and MAI, PbI$_2$, and DMSO (1:1:1 mol %). Perovskite layers were deposited on the top of 25×25 mm$^2$ glass by spin-coating at 4000 rpm (4000 ac) for 50 s. Chlorobenzene was used as anti-solvent and added just before the white solid begins to crystallize in the substrate. A mask with an interdigitated (ID) pattern (9 digits, 0.2 mm between digits,
0.2 mm width, and 7.8 mm length) was used. Gold was thermally evaporated (100 nm) at a base pressure of 6×10⁻⁶ mbar. The films were characterized by UV-Vis absorption spectra in a Cary 500 Scan VARIAN spectrophotometer (250-900 nm), obtaining the distinctive spectra with the corresponding absorption edge at 780 nm for MAPbI₃ with a bandgap of 1.60 eV (see Fig. S4). A mechanic Dektak 6M profilometer (Veeco) was used for film thickness measurement and the values were optimized by changing the spinning speed (see Fig. S5). Also, XRD patterns of MAPbI₃-films are included in Fig. S8. SEM analysis also shows the polycrystalline nature of the perovskite [Fig. 2(c)], and the ID geometric configuration [Fig. 2(d)] of the contacts. The examination of different thickness allows obtaining the optimum values (see Fig. S5). Direct impedance measurements of Fig. 1 and Fig. S1 were carried out by using a PGSTAT-30 Autolab potentiostat equipped with impedance module. Also ST transients, as in Fig. 2(b), were recorded with the same potentiostat. All electrical experiments were performed at room temperature in the air.

**FIG. 2** a) Sawyer-Tower circuit for charge transient measurements. b) Example of the charge transient response of a 320 nm-thick MAPbI₃ film registered in dark conditions. The applied rectangular voltage pulse of 1V-height is compared with the induced voltage V₀ (note the scale differences). c) SEM image of the top view of a MAPbI₃ film. d) SEM image of the perovskite interdigitated (ID) contacts.

Figure 3(a) shows a representative transient response, using the set-up in Fig. 2(a), occurring in a MAPbI₃ perovskite film of 320 nm-thick with an ID contact configuration. Here reference capacitors within the range of C₀ = 10 – 100 µF are employed, which are previously checked using impedance analysis (see Fig. S6), and show a plateau at the frequencies of interest (f < 1 kHz). By examining Fig. 3(a), one can observe charging signals upon application of a step bias of height V_app = 1 V in dark conditions. A necessary test to check experiment consistency consists of verifying
that $V_0 \ll V_{app}$. As observed in Fig. 3, $V_0$ inversely scales with the reference capacitor with values (in the mV range) much lower than the bias (1 V), in good accordance with the assumption $Q = C_0 V_0$ (see transfer function calculation in SI). This fact precludes the possibility of seeing the charging of the reference capacitor through the perovskite sample shunt resistance with time constant $\tau = R_{sh} C_0 \approx 10^3 - 10^4$ s, which would yield a saturation of the registered voltage as $V_0 \approx V_{app}$ at long time polarization. Contrary to this response, a rather steady-state voltage (charge) is attained (accumulated) for ~50 s-poling. This is particularly visible for $C_0 = 10 \mu F$.

The total amount of charge, calculated by using one exponential fitting, attains values within the range of $Q_{max} \approx 10 - 30$ nC [inset of Fig. 3b]. Remarkably, all curves collapse in the initial (~10 s) part of the transient, thus reinforcing our claim that $C_0$ charges as a consequence of the perovskite interface polarization and not through the shunt resistance. The reported dispersion in total accumulated charge can be understood in terms of the ionic and, presumably, reactive character of the polarization mechanism occurring at the interfaces (see below).

It is remarkable that the amount of charge does not match that expected from the polarization of perovskite bulk. As inferred from Fig. 1(b), the dielectric properties of the films give rise to a geometrical capacitance $C_g \approx 2.7$ pF, corresponding to the high-frequency plateau of the capacitance spectra. A value that would entail polarization charges of the order of pC (given 1 V-bias) as $Q \approx C_g V_{app}$. Such a small value is in contradiction to those actually encountered within the order of 10 nC [Fig. 3(b)]. Instead, that amount of charge correlates with the values attained by the low-frequency capacitance in Fig. 1(b): $C \approx 2$ nF at $f = 0.1$ Hz, and even higher capacitances are expected at lower frequencies.

By comparing capacitive and transient charging experiments, we can infer that the same mechanism in behind both responses. That mechanism manifests either as a low-frequency excess capacitance or as a steady-state charge induced by the applied voltage. The important difference between these two measuring techniques is that while impedance gives the differential, alternating-current small-amplitude response, transient charging is a large-amplitude procedure yielding in our experiments a permanent charge only explainable if a true polarization occurs. Therefore, a modulated or delayed injection current cannot be claimed as originating that observed steady-state response, simply because dc current is suppressed in the used setup. If the low-frequency excess capacitance was an apparent response, one would have expected polarization charges only caused by dielectric properties $Q \approx C_g V_{app}$, in opposition to that observed here.
The occurrence of polarized interfaces in PSCs were proposed some years ago. In the dark, the corresponding excess capacitance has been connected to the formation of double layer-like structures in the vicinity of the perovskite/contact interface in which mobile ions are piled up (Fig. 4) and shield part of the applied voltage. Excess dark capacitance of order 1-10 $\mu$F cm$^{-2}$ can be readily explained by this way. We can even roughly estimate the concentration of mobile ions contributing to the surface polarization at the outer electrodes. The perovskite total volume of our samples can be calculated (see Fig. S7) as $\sim 10^{-5}$ cm$^3$, which gives rise to mobile ionic densities of order $N \approx 10^{16}$ cm$^{-3}$, which only corresponds to the density portion effectively contributing to the interface polarization. That value results in agreement with recent and previous estimations.

Apart from purely electrostatic views accounting for the interface polarization, it has been also recognized that chemical interactions between mobile ions, photogenerated electronic carriers and contacting materials might give rise to the formation of dipole-like structures. A survey about the chemical reactivity of the perovskite/contact materials can be found elsewhere. It is emphasized by Bisquert and co-workers in that review paper that the kinetics of charging is hardly understood exclusively in terms of diffusion and double-layer formation. Moreover, interface reactivity forming local chemical bounds largely influence the resulting electronic and ionic overall dynamics. The complexity and lack of complete reproducibility inferred from the dispersion in the total accumulated charge of Fig. 3(b) should be related to the known chemical interaction between MAPbI$_3$ and gold electrodes, as recently highlighted.
FIG. 4 The process of interfacial polarization is schematized. Ionic mobile charges are driven by the applied electric field (dashed line) towards the contacts, causing a real polarization/accumulation of charge at the interface between Au contacts and MAPbI$_3$ film.

We remark that our findings corroborate the occurrence of a real polarization (charge imbalance) taking place in perovskite absorbers upon bias in the dark. On the contrary, several papers have recently proposed$^{21-23}$ that the commonly reported low-frequency capacitance features relate to the modulation of operating currents, either recombining or injecting currents, that evolve during the measurement. This effect creates out-of-phase signals not originated by charge polarization and wrongly interpreted in terms of the response of true capacitors. Following this view, it has been even claimed that measured capacitances are just apparent$^{23}$ and not connected to any carrier pileup or space charge formation, even under dark conditions.$^{23}$ Obviously, that explanation should be confronted with additional experiments, not only impedance responses. Here we have demonstrated the appearance of steady-state polarization voltages in the dark, easily interpreted by means of charged capacitors with values much larger than the film geometrical capacitance. We connect that polarization to the charging of perovskite/contact interfaces by mobile ions.
See the supplementary material for additional information on sample preparation and set-up checking and transfer function calculation.

Data available on request from the authors.

We acknowledge support from Horizon 2020 project (grant number 871336 - PEROXIS). M. G.-B. acknowledges Generalitat Valenciana for grant GRISOLIAP/2018/073. SCIC at UJI are also acknowledged. O.A. acknowledges the financial support from the VDI/VD Innovation + Technik GmbH (Project-title: PV-ZUM) and the SAOT funded by the German Research Foundation (DFG) in the framework of the German excellence initiative. J.C. acknowledges the partial support by project PUE-054-CONICET, Argentina.

References

1 Juan Bisquert, Emilio J. Juárez-Pérez, and Prashant V. Kamat, *Hybrid Perovskite Solar Cells: the Genesis and Early Developments 2009-2014*. (Fundació Scito, Valencia, 2017), p.150.

2 Martin A. Green, Anita Ho-Baillie, and Henry J. Snaith, *Nat. Photon.* 8 (7), 506 (2014).

3 Nam-Gyu Park, Michael Grätzel, Tsutomu Miyasaka, Kai Zhu, and Keith Emery, *Nat. Energy* 1, 16152 (2016).

4 Ying-Ke Ren, Xi-Hong Ding, Ya-Han Wu, Jun Zhu, Tasawar Hayat, Ahmed Alsaedi, Ya-Feng Xu, Zhao-Qian Li, Shang-Feng Yang, and Song-Yuan Dai, *J. Mater. Chem. A* 5 (38), 20327 (2017).

5 E. L. Unger, E. T. Hoke, C. D. Bailie, W. H. Nguyen, A. R. Bowring, T. Heumüller, M. G. Christoforod, and M. D. McGehee, *Energy & Environmental Science* 7, 3690 (2014).

6 N. J. Jeon, J. H. Noh, Y. C. Kim, W. S. Yang, S. Ryu, and S. I. Seok, *Nature Materials* 13, 897–903 (2014).

7 Rafael S. Sanchez, Victoria Gonzalez-Pedro, Jin-Wook Lee, Nam-Gyu Park, Yong Soo Kang, Ivan Mora-Sero, and Juan Bisquert, *Journal of Physical Chemistry Letters* 5, 2357–2363 (2014).

8 Emilio J. Juarez-Perez, Rafael S. Sanchez, Laura Badia, Germá Garcia-Belmonte, Yong Soo Kang, Ivan Mora-Sero, and Juan Bisquert, *J. Phys. Chem. Lett.* 5 (13), 2390 (2014).

9 Osbel Almora, Isaac Zarazua, Elena Mas-Marza, Ivan Mora-Sero, Juan Bisquert, and Germà Garcia-Belmonte, *J. Phys. Chem. Lett.* 6 (9), 1645 (2015).
10 Victor W. Bergmann, Yunlong Guo, Hideyuki Tanaka, Ilka M. Hermes, Dan Li, Alexander Klasen, Simon A. Bretschneider, Eiichi Nakamura, Rüdiger Berger, and Stefan A. L. Weber, ACS Applied Materials & Interfaces 8 (30), 19402 (2016).

11 Stefan A. L. Weber, Ilka M. Hermes, Silver-Hamill Turren-Cruz, Christopher Gort, Victor W. Bergmann, Laurent Gilson, Anders Hagfeldt, Michael Graetzel, Wolfgang Tress, and Rüdiger Berger, Energy & Environmental Science 11 (9), 2404 (2018).

12 Ronen Gottesman, Pilar Lopez-Varo, Laxman Gouda, Juan A Jimenez-Tejada, Jiangang Hu, Shay Tirosh, Arie Zaban, and Juan Bisquert, Chem 1 (5), 776 (2016).

13 Ronen Gottesman, Eynav Haltzi, Laxman Gouda, Shay Tirosh, Yaniv Bouhadana, Arie Zaban, Edoardo Mosconi, and Filippo De Angelis, The journal of physical chemistry letters 5 (15), 2662 (2014).

14 W. Tress, N. Marinova, T. Moehl, S. M. Zakeeruddin, Mohammad Khaja Nazeeruddin, and M. Grätzel, Energy & Environmental Science 8 (3), 995 (2015).

15 Rebecca A. Belisle, William H. Nguyen, Andrea R. Bowring, Philip Calado, Xiaoe Li, Stuart J. C. Irvine, Michael D. McGehee, Piers R. F. Barnes, and Brian C. O'Regan, Energy & Environmental Science 10 (1), 192 (2017).

16 Osbel Almora, Antonio Guerrero, and Germà Garcia-Belmonte, Applied Physics Letters 108 (4), 043903 (2016).

17 Isaac Zarazua, Guifang Han, Pablo P. Boix, Subodh Mhaisalkar, Francisco Fabregat-Santiago, Ivan Mora-Seró, Juan Bisquert, and Germà Garcia-Belmonte, J. Phys. Chem. Lett. 7 (24), 5105 (2016).

18 Sandheep Ravishankar, Osbel Almora, Carlos Echeverría-Arroll, Elnaz Ghabremanirad, Clara Aranda, Antonio Guerrero, Francisco Fabregat-Santiago, Arie Zaban, Germà Garcia-Belmonte, and Juan Bisquert, J. Phys. Chem. Lett. 8 (5), 915 (2017).

19 Osbel Almora, Pilar Lopez-Varo, Kyung Tae Cho, Sadig Aghazada, Wei Meng, Yi Hou, Carlos Echeverría-Arroll, Iwan Zimmermann, Gebhard J. Matt, Juan A. Jiménez-Tejada, Christoph J. Brabec, Mohammad Khaja Nazeeruddin, and Germà Garcia-Belmonte, Sol. Energy Mater. Sol. Cells 195, 291 (2019).

20 Adam Pockett, Giles E. Eperon, Nobuya Sakai, Henry J. Snaith, Laurence M. Peter, and Petra J. Cameron, Phys. Chem. Chem. Phys. 19 (8), 5959 (2017).

21 Daniel A. Jacobs, Heping Shen, Florian Pfeffer, Jun Peng, Thomas P. White, Fiona J. Beck, and Kylie R. Catchpole, J. Appl. Phys. 124 (22), 225702 (2018).

22 Davide Moia, Ilario Gelmetti, Phil Calado, William Fisher, Michael Stringer, Onkar Game, Yinghong Hu, Pablo Docampo, David Lidzey, Emilio Palomares, Jenny Nelson, and Piers R. F. Barnes, Energy Environm. Sci. 12, 1296 (2019).
23 Firouzeh Ebadi, Nima Taghavinia, Raheleh Mohammadpour, Anders Hagfeldt, and Wolfgang Tress, Nat. Commun. 10 (1), 1574 (2019).
24 M. Ershov, H. C. Liu, L. Li, M. Buchanan, Z. R. Wasilewski, and A. K. Jonscher, IEEE Transactions on Electron Devices 45 (10), 2196 (1998).
25 J. J. H. van den Biesen, Solid-State Electronics 33 (11), 1471 (1990).
26 Jorge García-Cañadas and Gao Min, Journal of Electronic Materials 43 (6), 2411 (2014).
27 C. B. Sawyer and C. H. Tower, Physical Review 35 (3), 269 (1930).
28 Hongxia Wang, Antonio Guerrero, Agustín Bou, Abdullah M. Al-Mayouf, and Juan Bisquert, Energy & Environmental Science 12 (7), 2054 (2019).
29 Luca Bertoluzzi, Caleb C. Boyd, Nicholas Rolston, Jixian Xu, Rohit Prasanna, Brian C. O’Regan, and Michael D. McGehee, Joule 4, 109 (2020).
30 Jan Pospisil, Antonio Guerrero, Oldrich Zmeskal, Martin Weiter, Juan Jesus Gallardo, Javier Navas, and Germà Garcia-Belmonte, Advanced Functional Materials 29 (32), 1900881 (2019).
31 Jordi Carrillo, Antonio Guerrero, Sara Rahimnejad, Osbel Almora, Issac Zarazua, Elena Mas-Marza, Juan Bisquert, and Germà Garcia-Belmonte, Adv. Energy Mater. 6 (9), 1502246 (2016).