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Organic and perovskite solar cells for space applications

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ABSTRACT

For almost sixty years, solar energy for space applications has relied on inorganic photovoltaics, evolving from solar cells made of single crystalline silicon to triple junctions based on germanium and III-V alloys. The class of organic-based photovoltaics, which ranges from all-organic to hybrid perovskites, has the potential of becoming a disruptive technology in space applications, thanks to the unique combination of appealing intrinsic properties (*e.g.* record high specific power, tunable absorption window) and processing possibilities. Here, we report on the launch of the stratospheric mission OSCAR, which demonstrated for the first time organic-based solar cell operation in extra-terrestrial conditions. This successful maiden flight for organic-based photovoltaics opens a new paradigm for solar electricity in space, from satellites to orbital and planetary space stations.

1. Advantages and challenges

Nearly every man-made device needs energy, most commonly in the form of electricity. This need travels along with the device, when we take it beyond the boundaries of Earth. To ensure longer lifetime and to reduce the load, solar powered satellites were introduced in the late fifties, shortly after the world wide announcement about successful solar energy harvesting [1]. PhotoVoltaics (PVs) thus allowed for truly renewable and infinitely abundant energy, the cost of which is determined only by the initial investment for the production of solar panels and, when envisioned as energy source for spacecrafts, their transport out of orbit. The cost of the latter increases quite rapidly with the mass of the object brought to space, which represents a key to the potential advantages of ultrathin solar cells. For this reason, already from the 1960s, space industry looked into the introduction of thin film CuS_2, CdS, and CdTe solar cells on the increasingly energy-demanding communications satellites, but eventually remained oriented on the more reliable Si [2].

Nevertheless, already in the fields of aerospace [3] and of organic and hybrid semiconductors [4,5], the specific power (W/kg) was proposed as a valid figure of merit to evaluate PV technologies for space missions. In this regard, Organic Solar Cells (OSCs) and hybrid organic-inorganic Perovskite Solar Cells (PSCs) – termed together as HOPV, Hybrid and Organic PhotoVoltaics – greatly outperform their inorganic counterparts [4,5]. They represent two novel branches of PV technologies, which saw their rise during the last decade (last few years in the case of PSCs) thanks to their potentially very low production costs. The high absorbance of the photo-active layers in HOPVs allows for efficient light collection within a few hundred nanometers of material, which leads to thicknesses one or two orders of magnitude lower than those of inorganic thin PVs. The rest of the layers making up the solar cell stacks are either as thin as or thinner than the absorbers, and the only thickness (and hence mass) limitation comes from substrate and encapsulation, which can consist of micrometers thick flexible plastic foil [4,5]. The specific power reached to date for perovskite (23 kW/kg) [4] and organic (10 kW/kg) [5] solar cells is thus over 20 or 10 times higher than what is required by some of the new missions which envision the need for lower weight and reduced deployment costs [2].

The high specific power is not the only appealing feature of these devices. The mentioned low cost fabrication originates from their intrinsic compatibility with low-temperature printing deposition techniques. They could thus be readily produced *in situ* (in/out of orbit or on a

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Table 1
For each solar cell type, we list the number (#) of tested devices and their average performance parameters before and after flight, as measured under an AM1.5G simulated solar spectrum with an irradiance of 1000 W/m^2 (only working devices were re-measured: the number of devices included in the statistics is lower for the after flight measurements than for the before flight measurements). Since measurements were carried out in different laboratories, testing conditions might slightly vary. Due to the lack of solar simulators at the launch site and to the need for early shipment of the samples, the measurements correspond to a few months before flight and a few weeks after flight.

Solar cell type	#	Before flight								After flight							
		J_{SC} [mA/cm^2]		V_{OC} [V]		FF [%]		PCE [%]		J_{SC} [mA/cm^2]		V_{OC} [V]		FF [%]		PCE [%]	
		Av.	St. Dev.	Av.	St. Dev.	Av.	St. Dev.	Av.	St. Dev.	Av.	St. Dev.	Av.	St. Dev.	Av.	St. Dev.	Av.	St. Dev.
$MAPbI_3$	32	21.4	0.6	1.0	0.0	69.7	3.3	14.6	1.1	19.3	4.9	0.9	0.1	49.4	20.6	9.3	5.4
PBDTTPD:$PC_{71}BM$	32	10.4	0.9	0.8	0.1	57.0	9.3	4.6	1.4	9.4	1.1	0.8	0.1	49.8	13.0	3.7	1.3
PCPDTQx(2F): $PC_{71}BM$	32	12.7	0.6	0.7	0.1	46.6	4.2	4.1	0.8	11.9	1.3	0.7	0.1	46.2	2.2	3.7	0.5
F4-ZnPc:C_{60}	96	10.6	0.2	0.7	0.0	57.7	1.0	4.4	0.1	11.5	0.2	0.7	0.0	54.7	5.5	4.5	0.5
DCV5T:C_{60}	48	10.7	0.1	0.9	0.0	57.1	1.8	5.4	0.1	11.7	0.1	0.9	0.0	56.7	0.5	5.9	0.1
Flexible module	16	5.0	0.6	6.0	0.1	53.8	0.6	1.6	0.2	4.1	0.2	6.0	0.1	47.6	2.0	1.2	0.1
Total	256																

foreign planet), or transported in rolls [6]. These characteristics are quite revolutionary with respect to the PV devices currently employed by the space industry. These are folded like *origami*, to save volume, and the ensemble of hinges and structural elements makes up for most of the total mass of the final array [2]. The possibility to readily replace panels by means of printing is also of great value if we consider the heavy mechanical damage (potentially destructive) everything faces when orbiting around the Earth, where thousands of pieces of debris larger than tennis balls travel at speeds of ~ 10 km/s [7].

Another feature, also leading to a great potential towards high Power Conversion Efficiencies (PCEs), is the possibility to tune the energy bandgap of organic and hybrid perovskite absorbers by changing the chemical composition of the materials. Choosing for a tailored absorption window allows to optimally combine OSCs and PSCs, with each other or with inorganic PVs, in tandem devices, aiming at an increased photon collection efficiency [8].

The drawbacks holding organics and perovskites from their exploitation out of Earth are linked to the devices limited reliability, which is a paramount concern in the space industry. While on one hand the advent of new materials, processing routes, and encapsulation strategies is sure to lead towards higher stabilities, another important side of the issue lies with stability evaluation itself. Novel PV technologies are still being tested under "rooftop" degradation conditions, which do not represent the actual stress factors faced when orbiting around the Earth, for example. Space devices have to withstand unearthly harsh environments, as high energy incident radiation (mainly protons, electrons, and electromagnetic rays), a wide temperature range, vacuum, or plasma [9], depending on where they will need to operate. For example, the surface of the moon, which could represent a suitable candidate for solar energy harvesting, sees temperature variations of roughly 300 K within a few hours, and receives a flux of particles of ~10^8 cm^{-2} s^{-1} [10]. Orbiting around the Earth together with the International Space Station would mean withstanding temperature cycles between 173 and 373 K every 45 min, plasmas, and a portion of the high energy charged particles radiation [7,11].

The ISOS standards [12] applied in the HOPV community are thus not sufficient to validate the degradation induced by space-related stress factors. For this reason, a few groups already started investigating the effects of high energy proton irradiation, with promising results both for all-organic [13–15] and for perovskite [16] devices. Reports on the degradation induced by wide and quickly varying temperature ranges are still missing, although insights into the effects of low operating temperatures are available from studies conducted for different aims [17]. The impact of vacuum and of plasmas on HOPVs is also unexplored, but its influence would be best countered by appropriate encapsulation and module design.

2. OSCAR: mission plan

Although HOPVs have a unique disruptive potential for space applications, to the best of our knowledge, these technologies have not yet been tested in real space conditions. The OSCAR [18] (Optical Sensors based on CARbon materials) mission was developed in order to demonstrate the feasibility of the use of novel generation carbon based (fully organic or hybrid organic-inorganic) solar cells for space applications. OSCAR thus fits between the huge aerospace potential of HOPVs and the lack of its testing, meaning to create a first bridge over this gap through an *in situ* study of the performance and degradation suffered by 256 solar cells (various types of OSCs and PSCs) during a stratospheric balloon flight. This pioneering investigation is, to this date, unique, because of the great challenge of reaching the stratosphere.

The experiment consisted in mounting several different HOPV devices as a load to a 35000 m^3 stratospheric balloon, launched in October 2016 from the Esrange Space Center, in the North of Sweden. The flight duration was limited to five hours, of which more than three in the stratosphere, reaching an altitude of 32 km (roughly 3 times higher than commercial aviation). Such an ambitious goal was attainable thanks to the support and guidance of several experts from European space-related organizations, through the REXUS/BEXUS program [19].

In order to study the performance and to screen the reliability of various materials, we selected samples of both small molecule based [20] (F4-ZnPc:C_{60} [21], DCV5T:C_{60} [22]) and polymer based [23] (PBDTTPD:$PC_{71}BM$ [24], PCPDTQx(2F):$PC_{71}BM$ [25]) bulk heterojunction solar cells, deposited *via* evaporation and spin-coating from solution, respectively. We also included a fully flexible, roll-to-roll printed, set of organic solar modules as well as spin-coated methylammonium lead triiodide perovskites ($MAPbI_3$). This wide selection of photo-active material types and deposition routes was chosen in order to cover the organic-based photovoltaics panorama as thoroughly as possible.

The flexible solar modules were purchased from InfinityPV, while the small molecule, polymer, and perovskite solar cells were prepared by the IAPP (TU/Dresden), UHasselt, and IMEC vzw, respectively. Further details on the absorbers and layer compositions are available in the Supporting information. Table 1 gives an overview of the performances attained by the various devices after preparation, as well as clearly indicating the total number of devices characterized during the experiment.

The selected solar cells and modules are shown in Fig. 1 as they were mounted for flight. The chosen methodology was to track the performances of the devices during flight, to obtain the evolution of the Maximum Power Point (or of other performance indicators) with time and against temperature. All data were acquired through a home built measurement unit, designed to meet the set design requirements. A