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Compatibility study towards monolithic self-charging power unit based on all-solid thin-film solar module and battery

Florian Sandbaumhüter [a, b], Solomon N. Agbo [a, *], Chih-Long Tsai [a], Oleksandr Astakhov [a], Sven Uhlenbruck [a], Uwe Rau [a], Tsvetelina Merdzhanova [a]

[a] *Institute of Energy and Climate Research (IEK), Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*
[b] *Faculty of Electrical Engineering and Information Technology, RWTH Aachen University, Germany*

HIGHLIGHTS

- PV-battery compatibility in all-solid monolithic integrated power unit is studied.
- Matching PV-battery I-V characteristics is critical for device performance.
- 3-Terminal integration concept is proposed as solution to PV-battery I-V matching.

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ABSTRACT

Aiming at the development of a monolithic integrated all-solid-state self-rechargeable power unit, we perform a V-I characteristics compatibility study for the integration of such a device having a thin-film silicon multi-junction photovoltaic (PV) module and a thin-film solid Li//lithium phosphorus oxynitride// $LiCoO_2$ battery. The battery and PV module are connected to mimic a monolithic module-to-storage cell device and the performance of this device in various temperature conditions has been tested. Few issues regarding the matching of the battery and PV module characteristics are identified for improvement. The concept of the integrated all-solid-state PV-battery solution appears viable especially in three-terminal device configuration.

1. Introduction

The number of low-power consuming electronics that are in use globally has rapidly increased in recent years. Electronics such as mobile phones, e-book readers, mp3 players, sensors etc. in use today are more than the world population [1]. Conventionally, these electronics are powered by internal rechargeable batteries which are energized by the traditional energy sources such as the grid. In order to sustain the increasing in-built functionalities of these devices, it is crucial to have a battery with high energy density [2–4]. Even though battery technology has significantly improved in terms of its energy density and the energy requirements of electronics is generally decreasing, recent developments in these consumer electronics and the “Internet of Things” make it imperative to have cheap, wireless and all-inclusive integrated power solution for all-time operation of these electronics devices [5,6].

Photovoltaic (PV) energy is a suitable energy harvester which can be directly utilized to charge a secondary battery. The stored energy in the battery can then provide energy for low-power electronics when there are low or no solar irradiation. Since PV energy is in general universally available, it can be particularly suitable for powering distributed electronics in hard-to-reach regions such as locations in deserts and mountains or in the applications where wireless operation of small devices like sensors is desirable for control of environment, industrial processes or smart cities. A compact and scalable power supply integrating PV energy harvester and storage cell would suit many of the listed small scale applications. In our earlier works we proposed a thin-film monolithically integrated device concept [7,8]. Thin-film silicon solar cells are particularly relevant for this integration because of their ability to deliver a range of voltages when deposited as multi-

* Corresponding author.
E-mail address: s.agbo@fz-juelich.de (S.N. Agbo).

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junction stack. Moreover, the current density of 3–4 junction cells is accordingly 3–4 times smaller when compared to single junction solar cell which simplifies current matching with a battery. With a thickness of a few micrometers, thin-film silicon solar cells fit the concept of compact PV-battery combination. Furthermore, this type of solar cell has good low light performance [9–11] which is relevant for real life applications, especially indoors. Thin-film lithium battery, on the other hand, is currently one of the most widely used batteries. It has high power, reasonable energy density and high cycle life with no memory effect [12]. For the integrated PV-battery unit all-solid-state lithium batteries are of the highest interest to realize most compact and robust solid state integrated device.

In this work, we test the performance of all-solid-state thin-film lithium battery and thin-film silicon module in an arrangement that mimics monolithic integrated module-to-storage device. In an earlier work, we have demonstrated the operation of cell-to-cell monolithic integration without control electronics [8]. This contribution, on the other hand, is focused on module-to-cell integration operated under different temperature conditions.

In order to provide additional flexibility in applications of the integrated device we propose a three-terminal concept for the monolithic integration as shown in Fig. 1. This concept allows for the use of charge control electronics if necessary or use of simplest mode of operation without charge control as described in Ref. [8].

2. Experimental

The experimental work carried out involved firstly the temperature-dependent characterization of the battery and the solar module as separate devices. Afterwards, the solar module was used to charge the battery. Depending on the required charging current and voltage of the battery, a specific solar module is chosen based on what it's short-circuit current, I_{sc}, and open-circuit voltage, V_{oc}, are at the maximum of the charging current and voltage, respectively. For optimum charging in direct connection, the solar cell voltage at maximum power point has to be tailored to match the plateau voltage of the battery. However, in this case we have adapted the solar cell open-circuit voltage to the end-charging voltage of the battery in order to avoid overcharging. For this work, the solar module V_{oc} (4.3 V) was matched to the maximum operating voltage (4.3 V) of the battery. The charge/discharge tests were performed with and without load at standard AM1.5 illumination.

The battery used for this work is commercially available all-solid thin-film lithium battery "EFL700A39" from STMicroelectronics. It consists of lithium (Li) anode, solid lithium phosphorus oxynitride (LiPON) glass electrolyte and lithium cobalt oxide ($LiCoO_2$, LCO) cathode [13]. The active area of the battery is estimated to be 5.3 cm^2. Its average discharge voltage is 3.9 V and can be operated in between 4.2 V and 3.0 V. The capacity of the battery was measured using discharge current density of 13.2μAcm^{-2} for different temperatures ranging from 20 to 50 °C with a step of 5 °C. Coulombic efficiency was calculated as a ratio of discharged capacity to the charged capacity. After the measurement, temperature was increased for 5 °C for the next measurement with 2 h dwell before measurement. The battery was in the discharged state before the measurements were conducted. A 2 h dwell time at each temperature was used to guarantee that the battery reaches its ambient temperature.

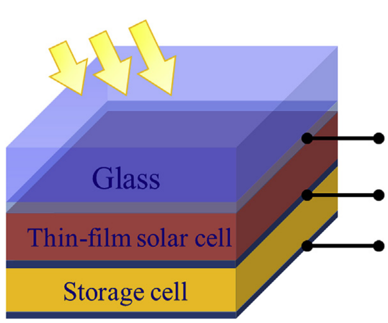

Fig. 1. Schematic of the 3-terminal monolithic integration concept which incorporates thin-film solar cell and an energy storage cell. The three terminals as shown allows for the application of charge-control devices thereby creating possibility to use varieties of solar cells and battery types.

Thin-film silicon solar modules consisting of two triple-junction PV cells connected in series are used. These triple-junction solar cells are prepared in superstrate p-i-n configuration on Asahi VU substrate. Top and middle cell consist of hydrogenated amorphous silicon (a-Si:H) and bottom cell consists of hydrogenated microcrystalline silicon (μc-Si:H) absorber layers. The silicon layers were deposited in a multi-chamber large area radio frequency plasma enhanced chemical vapor deposition system with shower head electrodes. More preparation details can be found in Refs. [7,8]. Aluminum doped zinc oxide in combination with aluminum layer constitute back reflector and back contact, respectively. Integrated series connection of both cells is realized through three laser scribing steps in between several deposition steps [14,15]. The module has an active area of 9.6 mm^2 that delivers under standard illumination a short-circuit current equivalent to the required battery charging current.

Current-voltage (IV)-curves are measured at AM1.5 illumination (AM1.5 spectrum, 100 mWcm^{-2}) with class-A sun simulator from Wacom, Japan. Due to solar cell degradation from the Staebler-Wronski effect [16], the solar modules were left under AM1.5 illumination for 100 h before measurements to stabilize parameters of the solar module. For the dark IV measurement the sun simulator was switched off and the set-up covered with black material to ensure that there are no incident lights. Table 1 lists the photovoltaic parameters of the used solar module before and after degradation showing the solar cell conversion efficiency η, fill factor FF (a ratio of the maximum power (I_{mpp}*V_{mpp}) from the solar cell compared to the product of the V_{oc} and I_{sc}), short-circuit current I_{sc}, open-circuit voltage V_{oc}, current at maximum power point I_{mpp} and voltage at maximum power point V_{mpp}. The temperatures for all measurements are controlled by water cooling system at the backside of the solar module. Experiments are carried out from 15 to 50 °C with a temperature step of 5 °C. Random sampling close to the solar module showed an accuracy of ±0.5 °C. The solar energy-to-battery charging efficiency η, which is the efficiency of the integrated device was determined as described in Refs. [17,18].

$$\eta = \frac{V_b \times C_b}{P \times A \times t \times 1/3600} \times 100 \quad (1)$$

where V_b, C_b, P, A, and t are the battery voltage (V) over the measurement interval t, battery charge increase (Ah), solar irradiance (Wm^{-2}), PV area (m^2) and the charging time (s), respectively. The solar-to-battery charging efficiency was determined per time interval (in this case every 1 s) using the actual measured values of current and voltage at the given time.

In order to test the charging process without charge controller,

Table 1
Photovoltaic parameters of stand-alone triple junction thin-film silicon solar module before (initial) and after (degraded) 100 h of light-soaking.

	η [%]	FF [%]	I_{sc} [mA]	V_{oc} [V]	I_{mpp} [mA]	V_{mpp} [V]
Initial	8.6	78.2	0.24	4.40	0.22	3.77
Degraded	8.1	74.5	0.24	4.34	0.21	3.67