



## Development towards cell-to-cell monolithic integration of a thin-film solar cell and lithium-ion accumulator



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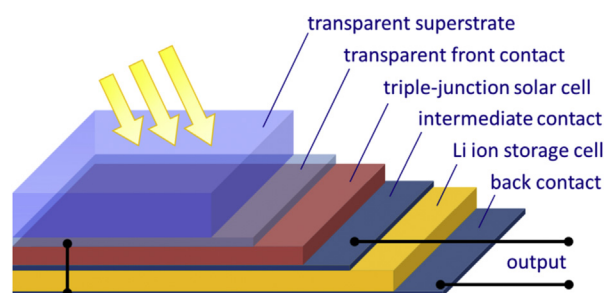
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### HIGHLIGHTS

- Potential of cell-to-cell PV-battery monolithic integration is demonstrated.
- Matching PV and storage cell JV characteristics is critical for device performance.
- Maximum solar energy-to-battery charging efficiency of 8.6% is obtained.

### GRAPHICAL ABSTRACT



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### ABSTRACT

This work focuses on the potentials of monolithic integrated thin-film silicon solar cell and lithium ion cell in a simple cell-to-cell integration without any control electronics as a compact power solution for portable electronic devices. To demonstrate this we used triple-junction thin-film silicon solar cell connected directly to a lithium ion battery cell to charge the battery and in turn discharge the battery through the solar cell. Our results show that with appropriate voltage matching the solar cell provides efficient charging for lab-scale lithium ion storage cell. Despite the absence of any control electronics the discharge rate of the Li-ion cell through the non-illuminated solar cell can be much lower than the charging rate when the current voltage (IV) characteristics of the solar cell is matched properly to the charge-discharge characteristics of the battery. This indicates good sustainability of the ultimately simple integrated device. At the maximum power point, solar energy-to-battery charging efficiency of 8.5% which is nearly the conversion efficiency of the solar cell was obtained indicating potential for loss-free operation of the photovoltaic (PV)-battery integration. For the rest of the charging points, an average of 8.0% charging efficiency was obtained.

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## 1. Introduction

Traditional power solution from stand-alone photovoltaic system includes solar module and battery module coupled via

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charging driver. Series connection of the solar cells in module provides flexibility in nominal output voltage while charge driving hardware controls the charging process [1,2] and prevents the battery from discharging through the solar cell in absence of sufficient illumination. The solution however may be suboptimal for small, portable, low power consuming devices. Aiming at ultimate compactness, simplicity and scalability we considered a concept of monolithic integration of lithium ion storage cell with thin-film silicon solar cell for low power consuming small-scale electronics.

Photovoltaic (PV) energy converters combined with storage devices are reported in literature for solar cells with capacitors [3–8], and with lithium ion storage [9–18]. Concepts of monolithic PV-battery cells have been published in the past [15–18] most often requiring intermediate control electronics. Direct stacking of the battery with solar cell provides ultimate compactness, scalability, and minimal loss between PV and battery cells. Disadvantages of the concept are absence of maximum power point tracking [19], and discharge through the solar cell without illumination. The former issue can be minimized with proper voltage matching between the solar cell and the battery whereas the latter point can be avoided in more complex stack with e.g. a Schottky diode layer between both devices [2]. Despite the straightforward design, realization of the concept is challenging firstly because of voltage and current mismatch between the solar cell and the battery. Common solar cells have output voltage of below 1 V whereas high energy density battery requires more than 3 V to be charged. On the current side the situation is opposite. Appropriate quality solar cells deliver much higher current densities than a monolayer of usual storage cells can accommodate. This difference in current density may reach several orders of magnitude and can at the moment only be completely eliminated with wrapping or stacking of a larger area storage cell.

Multi-junction thin-film silicon solar cells are attractive candidates for this integrated solution because they can provide a wide range of voltages [20,21]. More so, the current density of 3–4 junction cells is accordingly 3–4 times smaller as compared to single junction solar cells which simplifies current matching with a battery. With thickness of few micrometers thin-film silicon solar cells fit the concept of compact PV-battery combination. Moreover this type of solar cells has good low light performance [22,23] which is relevant for real life applications, especially indoors.

As a counterpart of the solar cell, a Li-ion battery with carbon coated Lithium iron phosphate ( $\text{LiFePO}_4/\text{C}$ , LFP) as cathode and Lithium titanate ( $\text{Li}_4\text{Ti}_5\text{O}_{12}$ , LTO) as anode is of interest [11,24–26]. The LFP/C electrode is one of the most promising electrodes widely used today because it has high electrochemical stability against over-charging and is available as commercial sheets with active carbon and binder. It is relatively cheap and made of nontoxic and abundant elements [27–30]. The LTO anode is mechanically very stable upon cycling ('zero-strain' material) and nontoxic with good cycling performance and high lithium ion diffusion coefficient [31–33]. A particular advantage of both electrode materials is their flat (dis)charge potential. There are also continued interests in sodium ion batteries because sodium is largely available and can be found everywhere. It has a great potential for cost-effective large-scale applications like integration with PV [34–36] and can be a subject for our future investigation.

In this work, we explore the feasibility and potential of using multi-junction solar cells based on thin-film amorphous and microcrystalline silicon to charge lithium ion cell in a simple cell-to-cell monolithic integration. At the present stage of our development, the solar cell has been connected directly to a Li ion cell as discrete units without control electronics.

## 2. Experimental

A schematic presentation of the simplest PV-battery device concept is presented in Fig. 1. It consists of a triple-junction silicon solar cell deposited on glass or other transparent substrate with a suitable transparent front contact and a battery deposited directly on the back contact of the solar cell.

Triple-junction solar cells are stacked single junction cells of p-i-n thin-film silicon solar cells [20,21] prepared in superstrate configuration (illuminated through the glass substrate). Top cell and middle cell consist of amorphous silicon (a-Si:H) layers and bottom cell consist of microcrystalline silicon ( $\mu\text{-Si:H}$ ). The silicon layers were deposited in a multi-chamber large-area radio-frequency plasma-enhanced chemical vapour deposition system with shower-head electrodes. The intrinsic absorber layers were deposited from a gas mixture of silane ( $\text{SiH}_4$ ) and hydrogen (H) while the p- and n-type layers were obtained by adding trimethylborane (TMB) and phosphine ( $\text{PH}_3$ ) as dopant gases respectively. The front contact as in Fig. 1 is fluorine doped tin oxide ( $\text{SnO}_2:\text{F}$ ) coated glass substrate type Asahi VU and the intermediate and back contacts are a stack of sputtered aluminum doped zinc oxide and silver ( $\text{ZnO:Al/Ag/ZnO:Al}$ ). The substrate temperature during deposition for all the component layers of each cell was 180 °C except for the intrinsic  $\mu\text{-Si:H}$  that was 145 °C. The plasma power density for the different i-layers varied between 0.018 and 0.32  $\text{W cm}^{-2}$ . More details about the solar cells are given elsewhere [20,37]. In order to obtain the necessary charging current, we have reduced the cells area (by laser scribing) to 0.1  $\text{cm}^2$  and the illumination intensity (by attenuating AM1.5 illumination using neutral density filters). The cells were characterized by a current-voltage measurement using a Wacom class A solar simulator under standard conditions (AM1.5 spectrum, 100  $\text{mW cm}^{-2}$  at 25 °C). The incident photon-to-current efficiency (IPCE) otherwise known as the external quantum efficiency *EQE* of the solar cells was determined using lock-in detection of a chopped monochromated light in the wavelength range: 300 nm–1100 nm. The *EQE* of each component cell was separately determined when the other sub-cells were saturated by the corresponding bias light [21].

A Swagelok®-type battery was prepared by using commercial LFP/C cathode (~2.2  $\text{mAh cm}^{-2}$ , Customcells, Germany) and LTO anode (~1.6  $\text{mAh cm}^{-2}$ , NEI corporation, USA). A glass fiber membrane served as separator and soaked with LP30 (DMC: EC 1:1 1 M LiPF<sub>6</sub>, dimethylene carbonate: ethylene carbonate, BASF USA) electrolyte. The theoretical voltage of the battery is about 1.90 V and is given by the difference of the cathode potential, 3.43 V (vs. Li/Li+) and the anode potential of 1.53 V (vs. Li/Li+). The surface area of LTO anode is 0.385  $\text{cm}^2$  which is same with the surface area of LFP/C cathode. To verify the electrochemical performance, charge/discharge test of the single LFP/C-LTO battery was conducted using a VMP3 potentiostat (Bio-Logic, France). The cycling was performed at different current densities between 1.2 and 2.2 V.

The triple-junction solar cell was connected directly to the Li-ion storage cell under attenuated AM1.5 illumination. This arrangement represents a cell-to-cell monolithic integration of the two devices. To test for energy losses hence the reliability of the integrated set-up, we have discharged the battery after approaching full state of charge (SOC) with the solar cell as load.

The solar energy-to-battery charging efficiency  $\eta$ , which is the efficiency of the integrated device was determined using the equation given in Refs. [11,13]

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

where  $V_b$ ,  $C_b$ ,  $P$ ,  $A$ , and  $t$  are the battery average voltage (V), battery

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