Fabrication of Scalable Indoor Light Energy Harvester and Study for Agricultural IoT Applications

M. Watanabe[1], A. Nakamura[1], A. Kunii[2], K. Kusano[2] and M. Futagawa[3]
[1] Business Development Project, LAPIS Semiconductor Co., Ltd. Yokohama, JAPAN
[2] Device Technology Division, LAPIS Semiconductor MIYAGI Co., Ltd. Furukawa, JAPAN
[3] Electrical and Electronic Engineering, Shizuoka University, Hamamatsu, JAPAN

E-mail: watanabe424@mnf.lapis-semi.com

Abstract. A scalable indoor light energy harvester was fabricated by microelectromechanical system (MEMS) and printing hybrid technology and evaluated for agricultural IoT applications under different environmental input power density conditions, such as outdoor farming under the sun, greenhouse farming under scattered lighting, and a plant factory under LEDs. We fabricated and evaluated a dye-sensitized-type solar cell (DSC) as a low cost and “scalable” optical harvester device. We developed a transparent conductive oxide (TCO)-less process with a honeycomb metal mesh substrate fabricated by MEMS technology. In terms of the electrical and optical properties, we achieved scalable harvester output power by cell area sizing. Second, we evaluated the dependence of the input power scalable characteristics on the input light intensity, spectrum distribution, and light inlet direction angle, because harvested environmental input power is unstable. The TiO_2 fabrication relied on nanoimprint technology, which was designed for optical optimization and fabrication, and we confirmed that the harvesters are robust to a variety of environments. Finally, we studied optical energy harvesting applications for agricultural IoT systems. These scalable indoor light harvesters could be used in many applications and situations in smart agriculture.

1. Introduction

In the IoT era, many sensor nodes with integrated energy harvesters were installed in many places and used in many applications. Since over one trillion sensors [1] per year is the scale required, facility usage and cost effectiveness is an important factor for practical energy harvesting applications. Indoor lighting power sources exist everywhere, although conventional silicon-type solar cells cannot be used in all applications because of their photoelectric conversion properties. Recently, next-generation solar cells such as dye sensitized solar cells (DSC) [2], organic thin films [3], and perovskite type [4] technologies have progressed, and they are expected to be applied for harvesting device relays because of their robustness to environmental lighting conditions and cost effective manufacturing processes.

“Scalability” is a keyword for lighting harvester devices. One type of scalability is output power scalability, for example output power linearity and voltage regulation flexibility, which depends on the external dimensions or design layout. For area scalability, DSCs commonly use transparent conductive oxide (TCO) substrates, but TCO is a high-cost material and has high sheet resistance and low transparency, so there is trade-off between efficiency and cell area. The other type of scalability is input power scalability, i.e., the dependence on environmental conditions such as light power intensity, wavelength, and incident angle. These two types of scalability are very important to expand IoT energy harvesting applications.

Journal of Physics: Conference Series **660** (2015) 012110 doi:10.1088/1742-6596/660/1/012110

There are many IoT sensing applications and many environmental conditions in each case. IT agricultural sensing is one representative application, and cultivated fields are exposed to a variety of environment lighting conditions from outdoor farming under the sun to indoor plant factories under LED lighting.

In this paper, scalable indoor light energy harvesting devices were fabricated by MEMS and printing hybrid technology, and harvester devices were evaluated under a variety of environmental conditions for agricultural IoT sensing applications.

2. Experiment

Fabrication was performed as follows. We used paste to fabricate a nano-porus TiO_2 layer and a Ru-based metal complex for the dye sensitizer. TiO_2 layer patterning was performed by a room-temperature nanoimprint process. The substrate metal mesh material was a titanium-based film.

The devices were irradiated by 100 mW/cm^2 with a light source simulating AM 1.5 global solar radiation. The current-voltage curves of the harvesters were measured with a semiconductor characterization source meter system at room temperature with masks under illumination. The shape analysis was performed with scanning electron microscopy (SEM; Hitachi, S-5000), the electrical properties were characterized by the sheet resistance, and the optical properties were measured with a spectrophotometer (Eiko-seiki, PSL 100).

3. Results and discussion

3.1 Device fabrication

First, we developed the cell material and process. DSC harvesters are mainly fabricated via screen printing. Figure 1 shows the conventional structure with a TCO substrate. We have developed TCO-less [5] process with a micro mesh metal structure, as shown in figure 2. Figure 3 is the typical fabrication result for a titanium-based metal mesh, which has low sheet resistance and high visible light transparency.

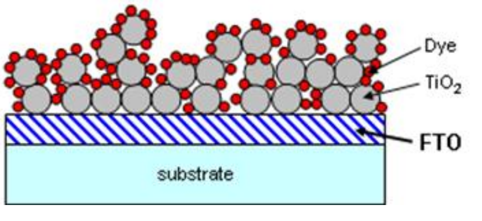

Figure 1. Conventional DSC structure

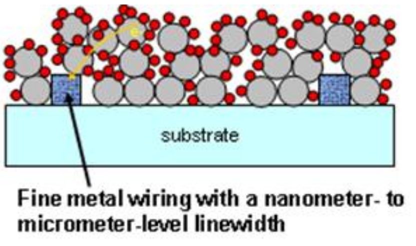

Figure 2. TCO-less structure

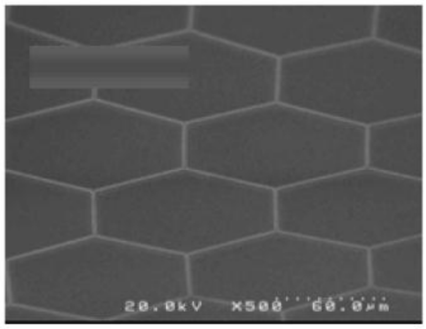

Figure 3. Fabrication of honeycomb mesh

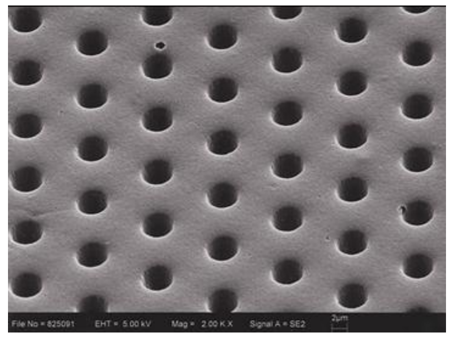

Figure 4. Hole array nanoimprinting

We fabricated TiO_2 electrodes and patterned a nanometer- to micrometer-scale structure that was designed for optical optimization and fabrication dye absorption process tact time. Figure 4 shows the hole array pattern fabricated by nanoimprint technology. The imprint process was carried out on coated TiO_2 paste at room temperature.

Second, we designed and fabricated the harvester module for a wearable thin film with a substrate thickness of 200 µm (figure 5a), a module for mobile use that was 40 mm by 40 mm (figure 5b), and a module for power generation that had a large area of 120 mm by 120 mm (figure 5c).

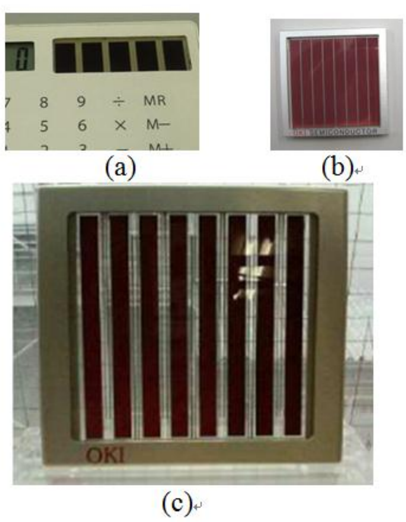

Figure 5. Module prototype of (a) a thin film module, (b) a 40 mm by 40 mm mobile use module, and (c) a 120 mm by 120 mm large area module.

3.2 I-V characteristics and scalability

The I-V output characteristics of chips with a variety of cell areas were estimated by cell fabrication and compared to the properties of a 5 mm square small test cell chip. Figure 6 shows cell area scalability with the micro honeycomb mesh structure developed. The photo-electron

Journal of Physics: Conference Series **660** (2015) 012110 doi:10.1088/1742-6596/660/1/012110

conversion efficiency had a constant value that depended on the cell area. Therefore, we confirm that the cell output power scalability does not depend on cell size.

Typically, the DSC output voltage is approximately 0.6 to 0.8 V per cell. Therefore, for output voltage scaling, we designed a module layout with cells connected in series. The harvester module showed scalable linear output properties that depended on the cell number, as shown in figure 7. Thus, we designed many module types for many application specifications.

Figures 8 and 9 show the inlet lighting condition dependence of the output power density. We confirmed that the DSC harvester could demonstrate photon-electron conversion, even in the low-light intensity condition below 100 lux, and we also checked other light sources, a florescence light and an OLED, that indicated the same trend as the LED. According to the results for the incident light intensity and inlet angle dependency, the harvester developed is robust to environmental conditions.

Furthermore, this system could also be used for high-power-consumption applications, such as wireless power supply systems for smart phones [6]. Therefore, harvester output power scaling was accomplished by the hybrid fabrication technologies presented here.

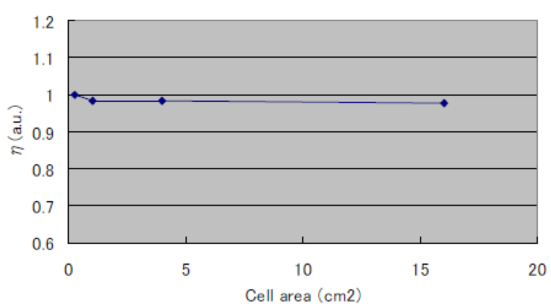

Figure 6. Cell area scalability with a micro mesh

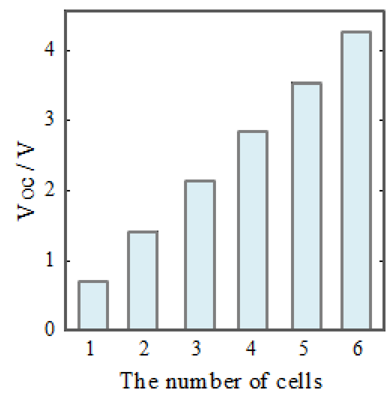

Figure 7. V_{oc} dependence on cell number

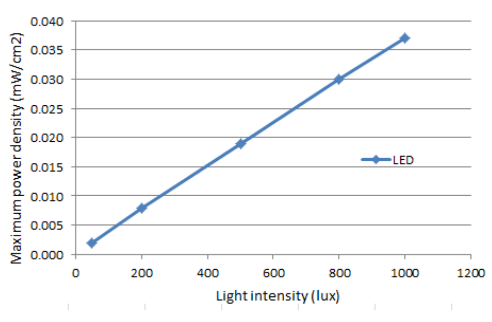

Figure 8. Maximum output power density

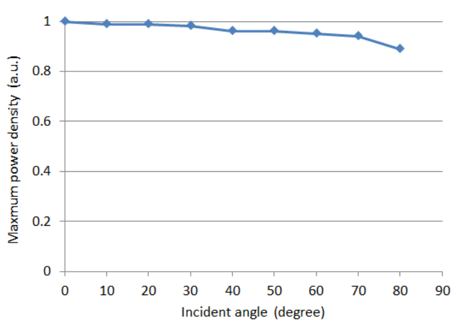

Figure 9. Light incident angle dependency

3.3 Study for agricultural IoT applications

IoT environmental sensing is used widely in outdoor and indoor environments. In an IT agricultural sensor network, sensor nodes are installed in various environmental lighting conditions such as those for outdoor cultivation, plastic light shield greenhouse farming, and indoor plant factories. We evaluated the environmental luminance intensity at a height of 30 cm from the ground. Illumination intensities were 80,120 lux at an outdoor cultivation farm, 40,280 lux at a greenhouse farm, and 17,500 lux in a plant factory on sunny days. On cloudy and rainy days or during morning and evening, the light intensity decreased to 1/10 to 1/100 of the intensity level under sunny daytime conditions. According to these results, the harvesters developed could cover the almost every agriculture environment application, even under conditions of low illumination intensity.

4 Conclusion

A scalable indoor light energy harvester was fabricated by MEMS and printing hybrid technology. It was evaluated for agricultural IoT applications under different environmental input power density conditions. We developed a TCO-less process with a honeycomb metal mesh substrate and TiO_2 hole array pattern fabricated by MEMS technology and evaluated a DSC module as a low-cost and "scalable" optical harvester device. This scalable indoor light harvester is robust to a variety of environmental conditions, and thus it could be used in many applications and environmental situations in IoT smart agriculture.

5 Acknowledgement

The authors would like to thank Professor Toyota of Tokyo University of Agriculture and Technology for agricultural application study and Professor Hirai of Osaka Prefecture University for the nanoimprint process.

References

[1] Trillion sensor universe web site, www.tsensorssummit.org/
[2] B. Oregon and M. Gretel, Nature 353 (1991) 737.
[3] C.W.Tang et al., Appl. Phys.Lett. 48 (1986) 183.
[4] A.Kojima, T.Miyasaka et al., J. Am. Chem. Soc. 131 (2009) 6050.
[5] M. Watanabe, H. Fujimaki et al., 25th EUPVSEC, 1DV4.5 (2010) 784.
[6] M.Watanabe, K Takeno et al., IEICE-EE, 2017-17, 110, 218 (2010) 7.