Edge-Illumination Scheme for Multi-striped Orthogonal Photon-Photocarrier-Propagation Solar Cells

A. Ishibashi, S. White, N. Kawaguchi, K. Kondo, T. Kasai

***Abstract*— Edge-illumination scheme was tried for a next generation solar cell that can optimize the light-absorption and the photocarrier-collection independently, with multi-semiconductor stripes in which photons and photocarriers move in orthogonal directions. In that scheme, the conversion efficiency remain high for the small active-layer thickness for which the conventional illumination scheme inevitably gives low conversion efficiency, suggesting the superiority of our new solar cell that operates under orthogonal photon-photocarrier-propagation mode.**

***Index Terms*—high efficiency, multi-stripe, solar cell.**

I. INTRODUCTION

We have an ultimate, i.e., safe and high-power, nuclear-fusion power-plant, the Sun, whose power being conveyed to Earth by solar photons through the space (vacuum, to a good approximation), the only problem is that the conversion efficiency of a detector, i.e., a solar cell [1],[2], is not high enough. Many kinds of solar cells, including those based on quantum dots [3], or on organic materials with novel configuration [4] have been studied, and achieving a high conversion efficiency even with using organic materials has been a focus of attention [5],[6]. So far it is difficult for conventional solar cells, including tandem solar cells [7], to convert the full spectrum of light into electricity. In this paper, we use edge-illumination scheme to investigate the feasibility of multi-striped orthogonal photon-photocarrier-propagation solar cells in which photons propagate in the direction orthogonal to that of photocarriers.

II. EXPERIMENTAL RESULTS AND DISCUSSION

In conventional solar cells, the sunlight impinge the solar-cell plane perpendicularly, and the photon's propagation direction is perpendicular to *pn* junction, while the photocarrier's diffusion/drift direction is along the largest gradient of the electric potential, i.e., vertical to the *pn* junction plane, and

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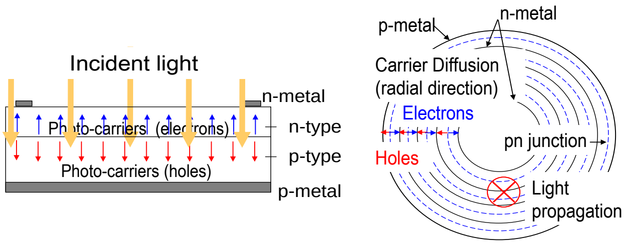

Fig. 1 *Cross-section of a conventional solar cell (left) and top view of orthogonal photon-photocarrier-propagation solar cell (right)*

thus is parallel to the direction of photon propagation as shown in Fig. 1(left). In general, on the other hand, we need a thick layer to efficiently absorb the solar light, but at the same time we have to make the layer thin enough to fully collect photo-generated carriers that has only finite life time. Thus, the conventional solar cells are outcome of compromise caused by a severe trade-off in determining the semiconductor layer thickness between light absorption and photocarrier collection, as shown by thick solid line in Fig. 2.

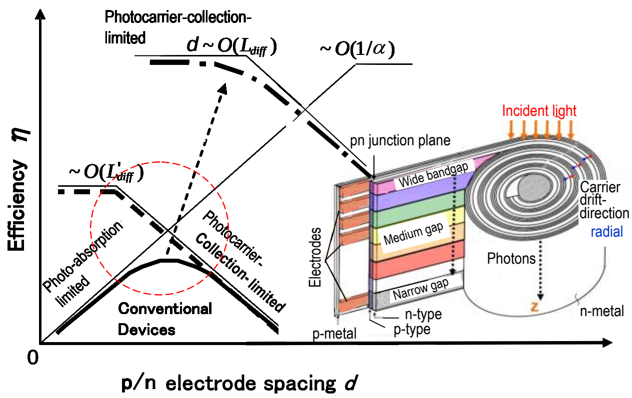

Fig. 2 *Conversion Efficiency vs. active-layer thickness (electrode spacing). The inset depicts the multi-striped orthogonal photon-photocarrier- propagation solar cell*

Situations would dramatically be changed in the orthogonal photon-photocarrier-propagation solar cell, because the photons propagate in the direction, not parallel, but vertical to that of the photocarriers'. One example of our new solar cells is based on the spiral heterostructure that is made by rolling up a *pn* junction sandwiched between anode electrode and cathode electrodes on a flexible substrate [8] resulting in a disk-like shape as shown in Fig. 1 (right) . In this solar cell, sunlight is to be shed vertically to the disk. As for the photocarriers, because the *pn* junction is spirally prepared, the photogenerated electrons and holes, move in the radial direction. The direction of photon propagation is parallel to the axis of the disk (*z*-direction) and is orthogonal to photo-carriers' drift direction. Thanks to the orthogonality, we can fully enjoy the freedom to make the disk thick enough to absorb all the photons keeping the distance between the *p*/*n* electrode distance (active-layer thickness) thin enough to allow most of photocarriers to reach out to the contact metals [8],[9]. Moreover, we can utilize the degree of freedom along z direction. By growing multiple semiconductor stripes, as shown in the inset of Fig. 2, we can prepare k semiconductor stripes, neighboring to each other, with different band gaps on the flexible substrate in such an order that the incoming solar photons first encounter the widest gap semiconductor, then narrower gap semiconductors, and the narrowest at bottom [10].

In the case of conventional solar cells, it is the best, but difficult, to obtain active-layer materials in which absorption coefficient α and mobility μ are both large enough. In our solar cell, we can virtually forget about the issue about α by setting the disk thickness in Fig. 1 (right), or by setting stripe width Wj in the inset of Fig. 2 as

$$W_j > 1/\alpha_j , \qquad (1)$$

where α_j is the absorption coefficient of the *j-th* semiconductor stripe. The best mode is to set W_j to be 3~6 times $1/\alpha_j$. By just concentrating on utilizing high mobility materials, we would be able to have, in our solar cell, the efficiency shown by dash-dot line in Fig. 2.

For proof-of-the-concept experiment, we have made a structure shown in Fig. 3. Two-hundred-micron thick PEN with 200-nm-thick IZO electrode is used as a substrate, on top of which 50-nm-thick PEDOT:PSS film and P3HT:PCBM layer with thickness d = 50~130 nm are spin-coated. Then Al electrode is prepared finally by vacuum evaporation. The sample is illuminated using a green laser having wavelength λ = 532 nm and power of ~1mW. As shown in Fig. 3, the light is shed from two different directions: one is a conventional illumination configuration in which photons impinge on the structure perpendicularly with respect to the layers (Fig. 3, left) and the other is the edge illumination configuration for which a modified system of microscopic photoluminescence (PL) is used with its focus on the edge surface. In Fig. 3 are shown cross section of the solar-cell structure (middle, top) and the laser spot (middle, bottom). The laser spot size, there, is roughly 30 μm in diameter with tailing skirt-part included but its strongest spot size is much sharper, a couple of microns in width. Because of this inherent spot size and the Gaussian beam waist located at the edge with focal depth of ~1um, we can regard that well-focused

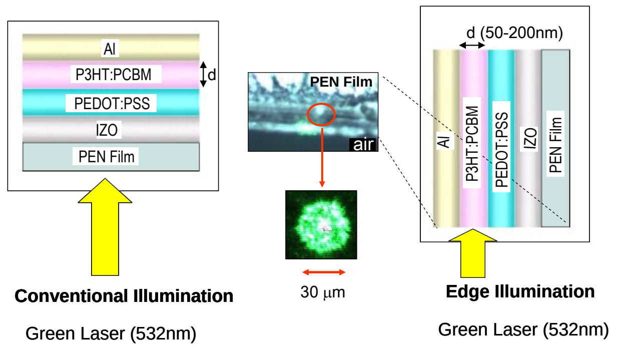

Fig. 3 *Photon injection scheme: a) conventional case and b) edge injection.*

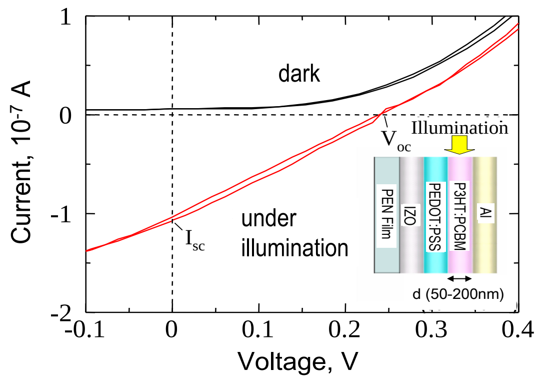

Fig. 4 *I-V characteristics of the cell in the dark and edge-illumination configuration.*

excitation photons are made go along the layer of P3HT:PCBM in the sample starting from the edge. Although the current is not so large, we do observe the photovoltaic characteristics under the edge illumination as shown in Fig. 4. Both in the dark and under the edge illumination, we have measured the *I-V* curve of the cell, and obtained open circuit voltages V_{oc}'s and short circuit current I_{sc}'s. For comparison, we also have measured *I-V* characteristics using the same solar cell sample under the conventional illumination configuration.

Based on those measurements, we plot the product $I_{sc} \cdot V_{oc}$ ($\propto \eta$: conversion efficiency) as function of the active-layer thickness *d* in Fig. 5. Blank circles are for the data obtained under conventional illumination and solid circles under the edge illumination. We can see In Fig. 5 that $I_{sc} \cdot V_{oc}$ start to decrease for *d* >100 nm and is good agreement with the *d*-dependence of the conversion efficiency observed using the same active-layer materials [6]. In Fig. 5, dashed is a line of log *d*, and the solid line is corresponding to the dependence of *exp*(-*d*/*L*) with *L*=30nm, which is in good accord with what was obtained before when considering the active-layer preparation [5,6]. The blank circles are, to a fairly good approximation, on the dashed line for $d \le 100nm$, and the solid circles are well on the solid line for $d \ge 100nm$, which is understood, using Fig. 2 (especially the encircled region), that the trade-off (denoted by the thick solid line) seen in the conventional illumination regime is lifted off in the edge illumination configuration, or in the orthogonal photon-photocarrier-propagation mode, as depicted by the

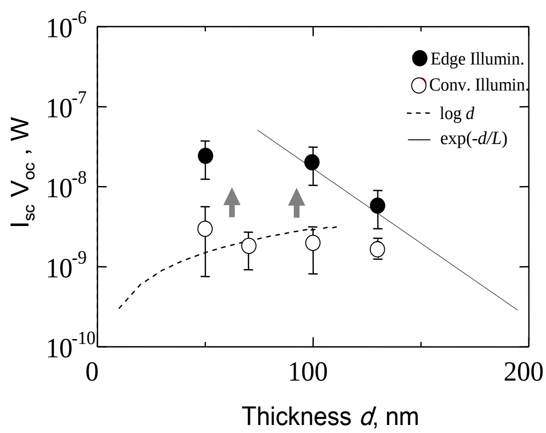

Fig. 5 *Conversion Efficiency vs. active-layer thickness (or electrode spacing) d, under two different illumination configuration.*

thick dashed line in Fig. 2. In this mode, the conversion efficiency η, remain high for a small *d* region for which the conventional illumination (or parallel photon-photocarrier-propagation mode) gives low η because of the loss of photons due to their penetration through the thin active-layers. This result manifests the superiority of the orthogonal photon-photcarrier propagation solar-cell anticipated in Fig. 2. In the orthogonal photon-photcarrier propagation solar-cell, we can concentrate on utilizing high mobility materials getting free from the constraint on α by making the disk-thickness several times 1/ α, and would fully enjoy high conversion efficiency depicted by dash-dot line in Fig. 2. The orthogonal photon-photcarrier propagation solar-cell would be able to be extended to a planar type [11] and are of potential interest for the next generation solar cells with a high efficiency.

III. Conclusions

We have investigated a multi-striped orthogonal photon-photocarrier propagation solar cell. Photons being impinging on the disk generating photo-carriers moving in the radial direction, the photons propagate in the direction orthogonal to that of the photo-carriers'. Because of the orthogonality, the new solar cell can optimize the absorption of light and the photo-carrier collection independently. By exploiting the degree of freedom along the axis perpendicular to the disk, we can convert the full solar spectrum into electricity resulting in high conversion efficiency. The connected solar cells of ours can convert virtually the whole spectrum of black body radiation into the electricity with a single output voltage, being a candidate for next generation solar cells with high energy conversion efficiency.

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Akira Ishibashi received the B.Sc. and M.Sc. degrees in physics in 1981 and 1983, respectively, and the Ph.D. degree in 1990, all from the University of Tokyo, Tokyo, Japan. During 1982–1983, he held a Research Assistantship at Lawrence Berkeley National Laboratory, Berkeley, CA, USA. In 1983, he joined the Research Center of Sony Corporation, Yokohama, Japan. He was a Visiting Faculty Member at Loomis Laboratory, Department of Physics, University of Illinois at Urbana- Champaign, during 1990-1991. He then returned to Japan where he, being engaged in physics and the development of ZnMgSSe-based blue/green laser diodes, achieved world-first RT CW operation in Sony. He was a Visiting Professor at Center for Interdisciplinary Research, Tohoku University, Sendai, Japan in 1998. In 2003 he joined RIES, Hokkaido University as a full professor. He is now leading Nanostructure Physics Lab in RIES. Since 2006, he has started Hokkaido Univ. venture company, C'sTEC Corporation, developing CUSP (clean unit system platform). His main targets are high-efficiency solar cells and versatile clean systems, not only to process those devices but also to help people live in a high standard.

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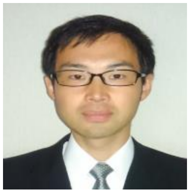

Nobuyoshi Kawaguchi is an engineer of Kyosemi Corporation, Japan. He is now engaged in development of optical communication devices and photodevices for sensors. He received the B.Sc. degree and M.Sc. degree from Hokkaido University in 2004 and 2006, respectively. He also received the Ph.D. degree from Hokkaido University in 2010. He joined Kyosemi Corporation as an engineer in 2011 and was engaged in development of spherical solar cells, Sphelar®. He was on loan to Sphelar Power Corporation during 2012- 2016 and was engaged in developing Sphelar®. He rejoined Kyosemi Corporation as an engineer in 2016.

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Tsuyoshi Kasai is engaged in processing solar cells based on Si and developing asymmetric waveguide to be coupled to multi-striped orthogonal photon-photocarrier-propagation solar cell. He received the B.Sc. degree from Hokkaido Institute of Technology in 2002. He engaged in device developments at Mitsubishi Electric Co. (2003-2005), Fuji Film Corp. (2006-2019), and is now at Hokkaido University (2011-).