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Symmetric and Asymmetric Wave-guides for Multi-striped Orthogonal Photon-Photocarrier-Propagation Solar Cells (MOP^{3}SC)

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Abstract

Waveguide-coupled orthogonal photon-photocarrier propagation solar cell (MOP^{3}SC) in which the photons propagate in the direction orthogonal to that of the photocarriers' is of potential interest for a high efficiency solar cell. We have studied feasibility of symmetric waveguides for MOP^{3}SC. The symmetric waveguide with refractive index modulation structure would not give a very high efficiency due to the reason originated from the spatial and time-reversal symmetries. To overcome the problem, we propose an asymmetric redirection waveguide consisting of periodic parabola mirrors.

Key words: solar cell, waveguide, symmetry

Introduction

We already have had an ultimate, i.e., safe and high power nuclear-fusion power-plant, the Sun. Its power being conveyed by solar light (photons), the only problem is that the transmission line is not good enough. Since the vast space between Sun and the Earth is almost completely vacuum except for a thin layer of air on the Earth's surface, the problem is that the conversion efficiency of solar cells is not high when we intend to use the solar energy in the form of electricity. Many kinds of solar cells [1-4] have been studied, and high conversion efficiency solar cells have attracted a lot of interest. So far it is difficult for conventional solar cells, including tandem solar cells, to convert the whole spectrum of light into electrical energy. This is one of the major challenges. In conventional solar cells, the photon propagation direction is orthogonal to a pn junction, and the diffusion direction of photo-carriers is parallel to that of the photon propagation (bottom left inset, Fig.1). Thus, in general, we need a thick layer to fully absorb the solar light, while we have to make the layer thin enough to collect photo-generated carriers as much as possible, because the carrier lifetime is finite. Thus, the conventional solar cells are with trade-off in determining the semiconductor layer thickness between the light absorption and the photocarrier collection.

Simulation and Discussion

In our orthogonal photon-photocarrier propagation solar cell in which, as shown in the bottom right inset of Fig. 1, the photons propagate in the direction orthogonal to that of the photocarriers. Our new system is based on the structure in which the MOP^{3}SC is connected to a diffraction waveguide that converts the three-dimensionally (3D) propagating sunlight into guided two-dimensional (2D) photons that eventually get into the pn junction from the edge as shown in the bottom right inset of Fig. 1. In this solar cell, photons being absorbed in the direction perpendicular to that of the carrier drift/diffusion, the aforementioned trade-off can be lifted. Thanks to the orthogonality, we can enjoy the freedom to make the stripe-width large enough to absorb all the photons keeping the distance between the pn electrodes (semiconductor layer thickness) small enough to allow most of photocarriers to reach out to the contact metals [5]. Further, by placing those multiple semiconductor stripes, neighboring to each other, with different band-gaps in such an order that the incoming guided photons first encounter the widest gap semiconductor, then medium-gap semiconductors, and the narrowest at last as shown in the bottom right inset of Fig. 1.

The planar type structure shown in Fig. 1 is of interest because of its capability of handling even rigid inorganic semiconductors, and using nano- and micro-structured waveguide-coupled type is now under investigation. In the system, since the multi-stripe structure is coupled to waveguide, further advancement would be possible. Not only the waveguide-coupled MOP^{3}SC can optimize the light absorption and the photocarrier collection, independently and

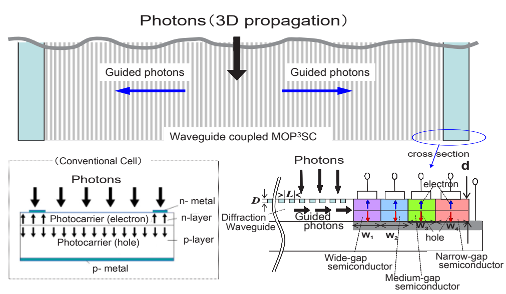

Fig.1 Waveguide-coupled multi-striped orthogonal photon-photocarrier propagation solar cell, conventional cell (bottom left), and cross section of MOP^{3}SC (bottom right). A target waveguide-size is tens of centimeters, and total width of the multi-striped semiconductor is ten to hundreds of microns.

simultaneously, converting virtually the whole spectrum of sunlight into electricity, but also serves as a highly efficient concentration photovoltaic system. Since the waveguide, shown in Fig. 1, converts 3D propagating photons coming with various tilt angles into 2D photons, we call it a redirection waveguide.

Since sunlight coming from various directions depending on when in daytime or how in weather, i.e., fine or cloudy, has to be handled, we need the redirection waveguide in the system shown in Fig. 1. The redirection waveguide should be so designed as to be able to convert the propagating 3D photons coming with a variety of tilt angles into guided 2D photons that are to be led eventually to get into the solar-cell-unit from its edge as shown with the horizontal arrows in the bottom right inset of Fig. 1. In fabrication, the edge of the solar-cell unit is to be treated with H_2O_2 plus HF solution so that ultralow reflectivity surface is achieved [6]. In short, the redirection waveguide has to have following two functions: 1) to make those photons coming with various angles go perpendicularly [as indicated by vertical downward arrows in the bottom right inset of Fig. 1] into the 2D waveguide, and 2) to change the photons' propagation direction from the perpendicular to parallel direction [as shown by the horizontal arrows in Fig. 1] with respect to the 2D waveguide plane.

We have been optimizing the redirection waveguide structure based on simulations using an *eigenmode* expansion propagation tool, a result of which has shown that by placing a structure having periodic parabola cross-section on one side of the slab, we can make the photons impinging with various incident angles propagate almost perpendicularly to the slab [7]. Thus the aforementioned first function of the redirection waveguide can be achieved well with the parabola cross-section structure (or with integrated-paraboloid-sheet, if possible) we can make virtually all the incoming photons impinge upon the 2D slab waveguide virtually at a right angle even for the sunlight in cloudy days. For the structure having periodic parabola cross-section, the reflectivity is controlled to be less than around 10% [7].

As for the second function of the redirection waveguide, by using the periodic refractive-index modulation [8] at the surface of 2D waveguide as shown with thin lines at the bottom surface of the slab waveguide in the insets of Fig. 2, we can make the photons (coming from beneath into the waveguide with a right angle) propagate laterally in the 2D waveguide as shown in the top right inset of Fig. 2. This structure, i.e., the second major part of the redirection waveguide consists, in simulation, of a 160-μm-long, 5-μm-thick slab having a refractive index n=1.33, and the adjoining periodic refractive-index modulation structure which is, for example, 0.50 μm wide, 0.769 μm deep, placed with a period, L, of 1.0μm, and having refractive index n=1.65, for which simulations result, i.e., the wavelength dependence of 2D photon's propagation efficiency is shown as a function of the incoming light wavelength with solid circles in Fig. 2. We show the propagation efficiency also for depth, D, of 1.15μm and L of 1.5μm (triangles) and for D=1.538μm and L=2.0μm (squares). With the aforementioned parabola-cross-section structure and the refractive-index modulation, we can redirect the photons with different wavelengths from 3D to 2D propagation with roughly in 50 to 60% in average. Full conversion from 3D to 2D is not yet achieved because the system, being based on diffraction, inevitably has a strong wavelength dependence. Also, we note that more fundamental problem with this approach is that since the refractive-index modulation structure in Fig. 1 has a left-right, i.e., spatial symmetry, the left-hand-side going photons (LHGPs) are as many as right-hand-side going photons (RHGPs). The fact that LHGPs can be regarded as time-reversal version of RHGPs means that the refractive-index modulation structure that makes those 3D propagating photons go right-hand-side in the 2D waveguide at the same time gets the two dimensional LHGPs back into the 3D propagating photons. Thus for the symmetric redirection waveguide, the 3D to 2D convertibility could not be very high.

Thus, we propose an asymmetric redirection waveguide as shown in Fig. 3, where 3D photons indeed go into the waveguide as in Fig. 1, but, here, unlike the situation in symmetric waveguide, the photons propagate toward right-hand side only in the 2D waveguide as shown in the top of Fig. 3. In the bottom left inset of Fig. 3, photons come from beneath along the vertical direction after passing through the aforementioned parabola cross-section structure (not shown in Fig. 3) and impinge on the periodic parabola mirrors as shown schematically in the bottom right inset. The periodic parabola are fabricated with 3D printing technology. Since the direction of the incoming photons from beneath are along the axis of the

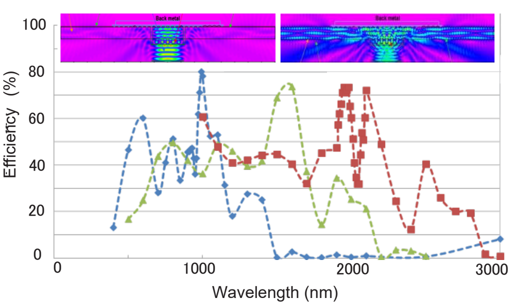

Fig. 2 Wavelength dependence of 2D propagation efficiency as a function of the incoming light wavelength. The inset show photons in the slab when poorly guide (top left) and when well guided (top right).

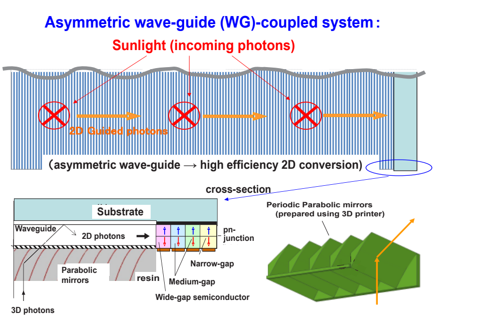

Fig. 3 Asymmetric waveguide-coupled MOP³SC, the cross-section of MOP3SC (down left), and a schematic view of the periodic parabolic mirrors (down right)

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parabola mirror, those photons can be led to focus in a spot in the 2D waveguide being attached to the periodic mirrors if we draw a cross-section as the bottom-left inset in Fig. 3. By carefully designing the cladding layer of the 2D waveguide with materials with anisotropy in its refractive index, based on the fact the photons are coming from a certain angle when seen from the focal point, we would be able to introduce those photons into the 2D waveguide, let them fully be reflected at the back cladding layer on the other side of the slab waveguide, and then make them impinge on the front cladding layer from backside, where the photons are to see different refractive index, because of the anisotropy in refractive index in the front cladding layer. Those photons could be managed to propagate in the 2D waveguide to reach out to the multi-striped solar cells located at the end of the slab waveguide.

Conclusion

We have studied feasibility of symmetric waveguides for orthogonal photon-photocarrier propagation solar cell (MOP^3SC) in which the 2D waveguided photons impinge on the solar cells located at the end of the slab waveguide. The photo-conversion efficiency of MOP^3SC with symmetric waveguide would not be so high because of the strong wavelength-dependence of the guiding efficiency if the refractive index modulation structure is used as the symmetric waveguide. More fundamental problem with the symmetric waveguide is that the left-hand-side going photons, being considered as the time-reversal version of right-hand-side going photons, are getting out of the 2D wave-guide to become 3D photons just in the reverse process of 3D photons turning into the 2D photons. To overcome this problem, we have proposed asymmetric redirection waveguide consisting of periodic parabola mirrors and the 2D waveguide with its cladding layer having anisotropy in refractive index. For the MOP^3SC, because of the orthogonality, the absorption of light and the photocarrier collection can be independently and simultaneously optimized without any trade-off. The waveguide-coupled MOP^3SC is expected to serve as a highly efficient concentration photovoltaic system with diffusive light convertibility. The waveguide-coupled MOP^3SC would serve as a high efficiency system in the near future.

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