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Optical Simulation for Multi-Striped Orthogonal Photon-Photocarrier-Propagation Solar Cell (MOP^{3}SC) with Redirection Waveguide

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Abstract We have calculated optical fields for 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'. By exploiting the degree of freedom along the photon propagation and using multi-semiconductor stripes in which the incoming photons first encounter the widest gap semiconductor, and the narrowest at last, we can convert virtually the whole spectrum of solar spectrum into electricity resulting in high conversion efficiency. The waveguide-coupled MOP^{3}SC can not only optimize the absorption of light and the photocarrier collection independently converting virtually the whole spectrum of sunlight into electricity, but also can serve as a highly efficient concentration solar-cell system with low temperature rise thanks to its minimal thermal dissipation and the diffusive-light-convertibility when used with the parabola cross-section structure on top of the waveguide. The waveguide-coupled MOP^{3}SC is also of potential interest as a high reliability system, because the high energy photons that can damage bonding of the materials, being converted into electricity already at upstream, never go into the medium or narrow gap semiconductors, resulting in low degradation of materials used in the MOP^{3}SC.

Keywords High efficiency · Solar cell · Photovoltaic device

1 Introduction

Energy and environmental issues have been increasingly serious, and development of highly efficient solar cells is of focus of attention. The high efficiency solar cells enable us to live elegantly on Earth with the ultimate, distant and safe nuclear power plant: the Sun. Many kinds of solar cells [1–4] have been studied so far, but in a conventional solar cell, the sunlight, being introduced orthogonally to the pn junction of the cell to generate photocarriers. The direction of photocarrier diffusion is parallel to that of the photon propagation. Thus, in general, we need a thick semiconductor layer to fully absorb the solar light, but on the other hand we have to make the layer thin enough to collect photo-generated carriers as much as possible, because the photocarriers have only a finite lifetime. Therefore, the conventional solar cells are with trade-off, in determining the semiconductor layer thickness, between the light absorption and the photocarrier collection.

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Situations are dramatically changed in our orthogonal photon-photocarrier propagation solar cell (MOP^3SC) [5]. Figure 1 shows a waveguide-coupled MOP^3SC, in which the sunlight, i.e., three-dimensional (3D) photon is received, as shown in the top of Fig. 1, with the large area of the waveguide and eventually propagate in the direction orthogonal to that of the photocarriers as shown in the bottom of Fig. 1. As a merit of MOP^3SC [5], by exploiting the degree of freedom along the photon propagation as well as using multi-semiconductor stripes in which the incoming photons first encounter the widest gap semiconductor, medium-gap semiconductors, next, and the narrowest at last, in the order of their energy bandgaps, we can convert the whole spectrum of sunlight into electricity resulting in high conversion efficiency. In this regime, originally spiral heterostructure-type solar cell was investigated [6]. Then planar type is of interest because of its capability of handling rigid inorganic semiconductors, and using nano- and micro-structured waveguide-coupled type is now under investigation. In the system shown in Fig. 1, since the multi-stripe structure is coupled to waveguide, further advancement is expected. Not only the waveguide-coupled MOP^3SC can optimize the absorption of light and the photocarrier collection independently and convert virtually the whole spectrum of sunlight into electricity, but also serves as a highly efficient concentration photovoltaic system. Since the waveguide, shown on Fig. 1, converts three dimensionally propagating solar light (3D photons) coming with various tilt angles into two-dimensionally propagating light-wave (2D photons), we call it a redirection waveguide.

2 Simulations and Discussions

Since sunlight comes from various directions depending on when in daytime or weather, i.e., fine or cloudy day, the redirection waveguide, in the system shown in Fig. 1, 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 led eventually to get into the solar-cell-unit from its edge as shown with the horizontal arrows in the bottom 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 [7]. In short, the redirection waveguide has following two functions: (1) to make those photons coming with various angles (denoted by thick oblique arrows in the bottom of Fig. 1) go perpendicularly (as indicated by short vertical arrows in 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 developing the redirection waveguide structure based on simulations using an eigenmode expansion propagation tool [8] that can provide steady-state solution of the optical field for the structure shown in Fig. 2, where the incident light is set to come from beneath as a plane-wave with an incident angles (a) of 30° and (b) of 60°. As shown by

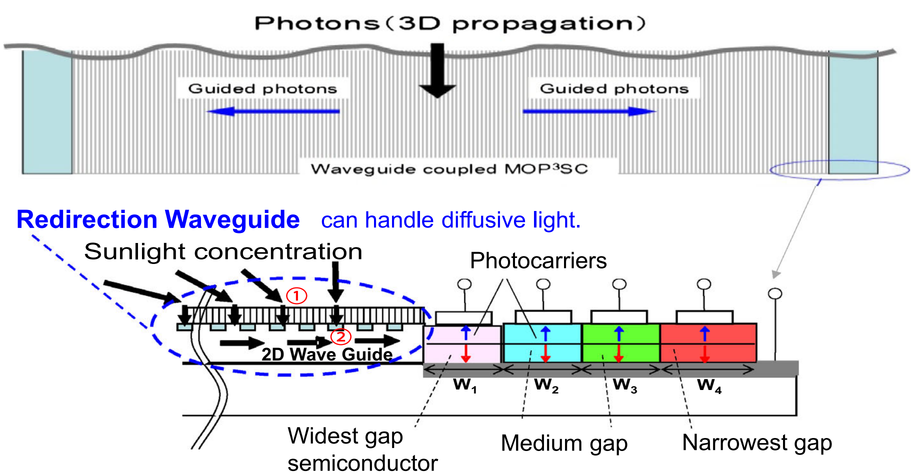

Fig. 1 Waveguide-coupled 4-striped orthogonal photon-photocarrier propagation solar cell

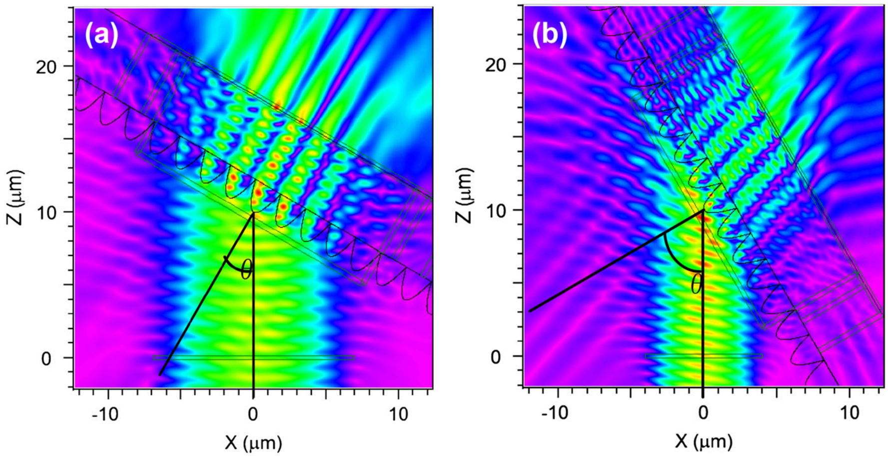

Fig. 2 Light propagation **A** with incident angle $\theta = 30°$ and **B** with incident angle $\theta = 60°$

thin curves in Fig. 2, by placing a structure having periodic parabola cross-section whose height and width are both 2.0 μm, and refractive index of 1.52, on one side of the slab, we can make the photons impinging with various incident angles propagate almost perpendicularly to the slab [9] as shown in Fig. 2, where the light intensity is indicated by the rainbow colors with red for high intensity and purple for weak. Figure 3 shows the *effective* refraction angle thus obtained as a function of the incident angle for various parabola structures with different width w and height h. The *effective* refraction angle is the angle of out-going light with respect to the normal line of the back plane, i.e., the plane of the slab without the periodic parabola structures. As shown in Fig. 3, the effective refraction angle, being less than that for the case without the parabola structure, can be set below $\sim 10°$ for $\theta_0 < 60^{\mathrm{o}}$. Thus the aforementioned first function of the redirection waveguide could be achieved well with the parabola cross-section structure (better with integrated-paraboloid-sheet, if available) 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. Then we have estimated how much of the incident light can actually go into the redirection waveguide with those effective refraction angles. In. Figure 4 we show the calculated reflectivity for the structure having periodic parabola cross-section whose height and width are both 1.0 μm. As seen in Fig. 4, the reflectivity is controlled to be less than around 10% (in particular for wavelengths $\lambda = 0.5$–1.0 μm) for $\theta_0 < 60^{\mathrm{o}}$, which mean that we can operate the system with such a low reflectivity for a wide span of the daytime, i.e., from 8 am to 4 pm. For the structure shown in Fig. 2, i.e., for the parabola cross-section whose height and width are

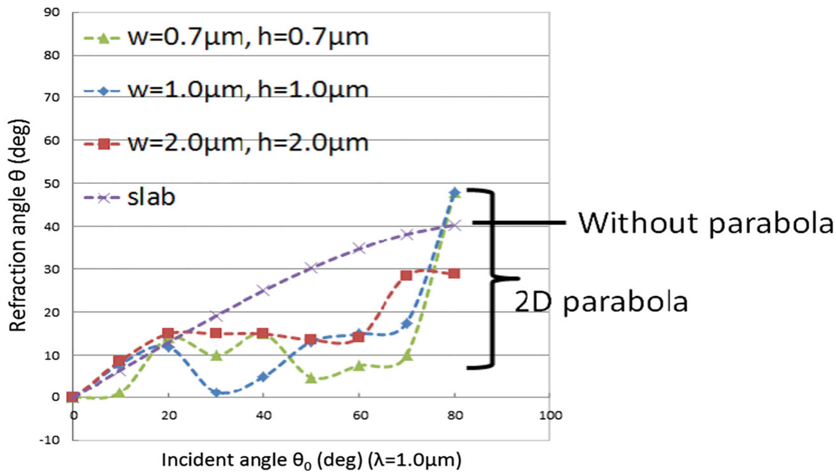

Fig. 3 Effective refraction angle for the case with parabola cross-section structure for various incident angles

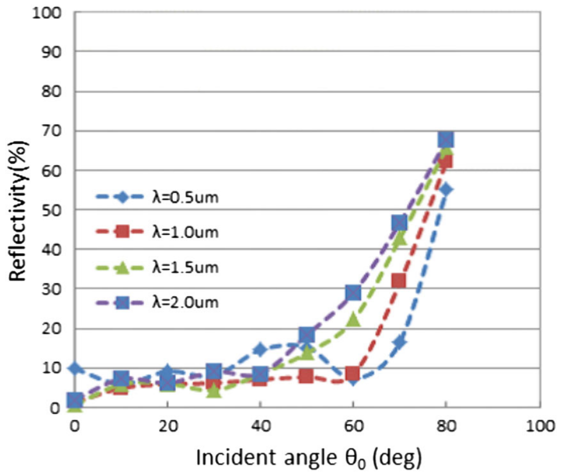

Fig. 4 Reflectivity of the redirection waveguide as function of the incident angle

both 2.0 μm, the reflectivity slightly increases and is around 10–11%.

As for the second function of the redirection waveguide, by using the periodic refractive-index modulation [10] at the surface of 2D waveguide as shown with thin lines at the bottom surface of the slab waveguide in the top of Fig. 5, we can make the photons (coming from beneath into the waveguide with a right angle) propagate laterally in the 2D slab waveguide. 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-m_2 index modulation structure which is, essentially a

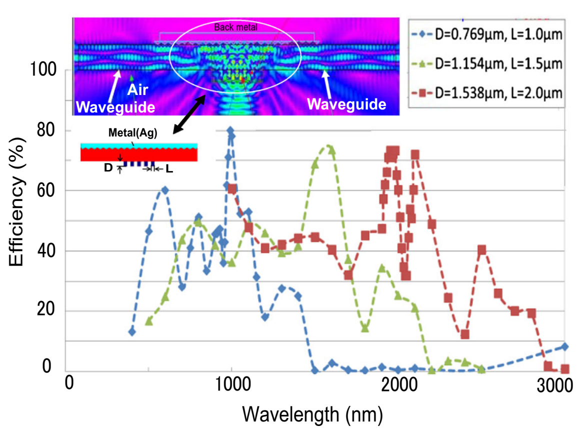

Fig. 5 Wavelength dependence of 2D propagation efficiency as a function of the incoming light wavelength. The *inset* shows 2D photon-propagation in the waveguide

"line and space" structure with the line width L being set equal to the space. In one case, the depth D of the structure (or the height of the line) is 0.769 μm and the line is with L of 1.0 μm and refractive index n of 1.65. Figure 5 shows is the 2D photon propagation efficiency as a function of wavelength. The efficiency is high around 80% at wavelength of around 1000 nm, for which the 3D photon is well converted to 2D photons, and also the 2D photons then propagate in the 2D waveguide with little loss. In Fig. 5, we also show the results for D of 1.154 μm and L of 1.5 μm and also for $D = 1.538$ μm and $L = 2.0$ μm. As seen in Fig. 5, the "sweet spot" of propagation efficiency moves to longer wavelength region as the line-and-space width increases. With the aforementioned parabola-cross-section structure and the refractive-m_2 index modulation structure, we can redirect the photons with different wavelengths from 3D to 2D propagation with roughly in 50–60% in average. Full conversion from 3D to 2D is not yet achieved because the system, being based on diffraction, inevitably has a large wavelength dependence. When the 3D to 2D photon conversion and the 2D-photon propagation efficiency are high enough, the limiting energy conversion efficiency would be about 50% without concentration and 60% for 1000 suns [6].

Those redirected photons now go into the solar-cell unit placed at the edge of the 2D waveguide along its pn junction plane, propagating in the direction orthogonal to that of the photocarriers' as desired (see Fig. 1). Thus, the photons being absorbed in the direction vertical to the carrier drift/diffusion, the aforementioned trade-off can be lifted, thanks to the orthogonality. 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 Fig. 1, we can virtually convert the full spectrum of sunlight into electricity [6]. We have been trying SiGe/Si/SiC as a three-striped structure for the MOP^{3}SC [11]. In the waveguide-coupled MOP^{3}SC, as seen in Fig. 1, all the photons that impinge upon the waveguide surface go into the multi-striped solar cell structure placed at the edge of the waveguide. The targeted size of the waveguide is roughly the size of a business card and the thickness of the solar-cell unit is tens of microns. Thus, the waveguide-coupled MOP^{3}SC is to serve as a concentration photovoltaic system typically operating under a few hundreds to a thousand suns. The waveguide-coupled MOP^{3}SC can not only optimize the absorption of light and the photo-carrier collection independently converting the whole spectrum of sunlight into electricity, but also serve as such a highly efficient concentration photovoltaic system with low temperature rise thanks to its minimal thermal dissipation plus its best match with heat-sinks to sandwich the very thin and flat multi-striped semiconductors as well as with the diffusive light convertibility when used with the parabola cross-section structure or the integrated-paraboloid-sheet on top of the waveguide. The possible heat-sinking from both sides is in marked contrast to the conventional concentration system for which the heat-sinking is only available from the back side of the solar cell. The waveguide-coupled MOP^{3}SC is also of potential interest as a high reliability system, because the high energy photons that can damage the bonding of the materials, being converted into electricity already at upstream in the wide-gaped semiconductor cell, never go into the medium or narrow gap semiconductors.

3 Conclusion

We have calculated optical fields for 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'. We have investigated the waveguide (redirection waveguide) that concert 3D propagation sunlight into 2D photons, which eventually go into the multi-striped semiconductor solar-cell units set at the edge of the waveguide. Because of the orthogonality, the newly proposed solar cell can optimize the absorption of light and the photo-carrier collection independently and simultaneously without any trade-off. By exploiting the degree of freedom along the photon propagation and using multi-semiconductor stripes in which the incoming photons first encounter the widest gap semiconductor, and the narrowest at last, we can convert the whole spectrum of solar spectrum into electricity resulting in high conversion efficiency. The waveguide-coupled MOP^{3}SC is also of potential interest as a high reliability system, because the high energy photons that can damage bonding of the materials, being converted into electricity already at upstream, never go into the medium or narrow gap semiconductors, resulting in low degradation in a-Si or organic materials used in the MOP^{3}SC. Thus, the waveguide-coupled MOP^{3}SC would serve as an ultimate high efficiency *all-in-one* system in the near future.

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