

New solar cell and clean unit system platform (CUSP) for earth and environmental science

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Abstract. We have investigated InGaN-based multi-striped orthogonal photon-photocarrier propagation solar cell (MOP³SC) in which sunlight propagates in a direction being orthogonal to that of photocarriers generated by the sunlight. Thanks to the orthogonality, in MOP³SC, absorption of the sunlight and collection of the photocarriers can be simultaneously and independently optimized with no trade-off. Furthermore, 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 solar spectrum into electricity resulting in the high conversion efficiency. For processing MOP³SC, we have developed Clean Unit System Platform (CUSP), which turns out to be able to serve as clean versatile environment having low power-consumption and high cost-performance. CUSP is suitable not only for processing devices, but also for cross-disciplinary fields, including medical/hygienic applications.

1. Introduction

Functional new devices and systems in materials/biological science, information technology, renewable energy, and environmental engineering have been of increasing importance. In research and development of those highly functional devices and systems, it seems convenient for us to investigate the systems in atom-bit-energy/environment (ABE²) four-dimensional space [1]. We have been studying quantum-cross devices in atom-bit (AB)-plane and multi-striped orthogonal photon-photocarrier- propagation solar cell (MOP³SC) in bit-energy (BE)-plane. We are at full notice that the high efficiency solar cell serves as a key device of electronics, i.e., a ubiquitous energy source for communication and the data, obtained exploiting highly clean environment realized by clean unit system platform (CUSP) [2], being available through information technology (IT) network would mean much for all of us in keeping ourselves in good health condition especially in a country like Japan where elder people is increasing in number as a generation. This would be the case for other large-population countries, in coming decades. Although many kinds of solar cells [3-5] have been studied, and high conversion efficiency solar cells have attracted much interest, it is not easy so far for



conventional solar cells, including tandem solar cells, to convert the whole optical spectrum of the Sun into electricity. In this paper, we report the current status of our waveguide-coupled MOP³SC whose solar cell parts, being made based on InGaN [6], are to be processed in CUSP and that of the potentially important CUSP application as a platform for sleep analysis.

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. Thus, in general, especially for indirect bandgap materials, 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 serious trade-off in determining the semiconductor layer thickness between the light absorption and the photocarrier collection. Here importance of edge injection of photons into the planer pn junction has been noticed [7]. For this purpose, since the edge is, by definition, very small compared to the planer size of the solar-cell, we need some apparatus to turn the spatially propagating three-dimensional (3D) photons into two-dimensional (2D) photons confined in a thin region that matches the size of the edge. For the 3D to 2D transformation, diffraction scheme plus planer waveguide seemed effective [8], but in reality it is not, because of symmetry issues. The structure used to cause the diffraction has spatial (left-right) symmetry, thus a half of 3D photons, after diffraction, become left-going 2D photons in the planer waveguide, while the rest half the right-going photons [8]. Because of time-reversal symmetry, the left-going photons, are now able to be considered as the time-reversed version of right-going photons that has turned into 2D from 3D by diffraction as time goes by, and then they turn into 3D from 2D by the same diffraction-causing structure, i.e., diffracted back to 3D space from the planer waveguide. Full 2D confinement is very difficult in the symmetric diffraction scheme.

2. A new high efficiency solar cell

Situations are dramatically changed in the structure shown in figure 1, i.e., the case of MOP³SC with an asymmetric redirection waveguide (ARW) [9]. With one example of the ARW, as shown in the bottom left inset of figure 1, the incoming photons first meet periodic parabola mirror, the photons make focus in the asymmetric waveguide, and, being fully reflected, propagate to the right-hand side only. The guided 2D-photons eventually get into the edge of the wide-gap semiconductor, then medium gaped ones, and finally the narrow gap material, in parallel to the pn junction planes as shown in the bottom left inset of figure 1. The direction of the photon propagation is orthogonal to that of the photocarriers that moves perpendicular to the pn junction plane. Thus, we call this system multi-striped orthogonal photon-photocarrier-propagation solar cell (MOP³SC), and it is connected to the ARW, in this example, consisting of the periodically placed parabolic mirrors and the 2D waveguide as shown in figure 1. In this solar cell, photons being absorbed in the lateral direction which is perpendicular to the direction of the carrier drift/diffusion, the aforementioned serious trade-off can be lifted, thanks to the orthogonality of photon-photocarrier propagation directions. We can enjoy the freedom to make the stripe wide enough to absorb laterally all the photons keeping the semiconductor layer (the p/n electrode distance) thin (short) enough to allow most of photocarriers to reach out to the contact metals. As stated above, 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, we can virtually achieve full conversion of sunlight spectrum into electricity. Note that our system being a tandem structure connected, not in serial, but in parallel, usage of many bandgaps is easier as long as materials with those bandgaps available. In this sense, for the MOP³SC of ours, InGaN [6,10] is a promising candidate among many inorganic semiconductors. Ideally, we could obtain the energy conversion efficiency as high as ~60 % and 75% when using, respectively, four and ten stripes of semiconductors for the concentrated sunlight [7].

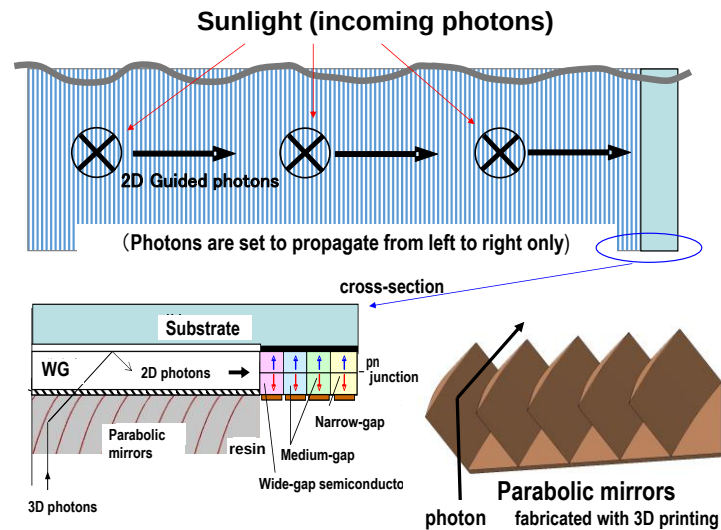


Figure 1. Waveguide (WG)-coupled multi-striped orthogonal photon-photocarrier-propagation solar cell (top view), cross-section (bottom left), and periodic parabolic mirrors (bottom right). WG size is tens of centimeters, and total width of the multi-striped semiconductor is tens to hundreds of microns.

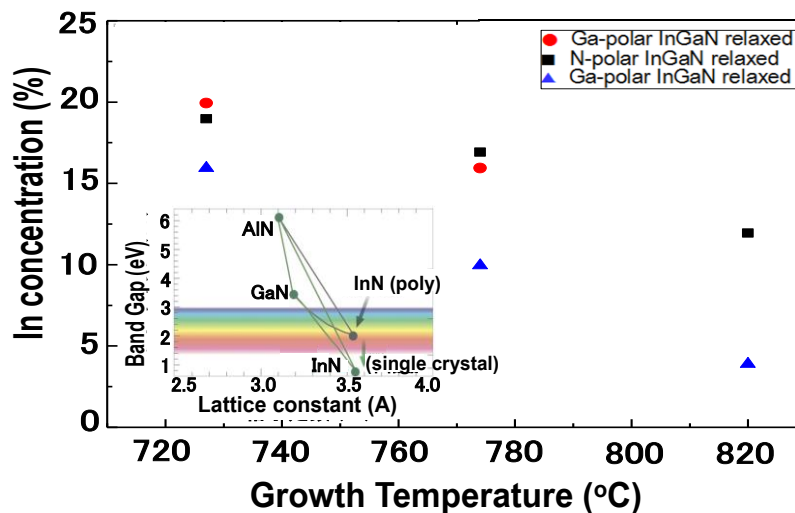


Figure 2. Growth temperature dependence of Indium composition in InGaN layers.

The usage of such a number of semiconducting materials would be unrealistic in conventional serially connected tandem structures, that number of pn junctions and accompanying tunnel junctions are very difficult, but is realistic in the InGaN-based MOP³SC, because such many number of stripes, i.e., various In concentrations in the lateral direction, could be provided in a single epitaxial process, for example, by changing the substrate temperature in that lateral direction in growing InGaN. Figure 2 shows the growth temperature dependence of in composition in InGaN layers [10]. Thus, by deliberately giving temperature difference laterally in the substrate, we would be able to obtain graded In composition in a single InGaN growth. Then we are to put electrode in the direction perpendicular to the temperature gradient, i.e., the direction along which the gradient of Indium composition is zero. The number of the electrodes depends on how large the composition difference is, and also on practical lithographical dimensions. The number can be much larger than that of component cells in

the conventional tandem solar cell. InGaN-based MOP³SC with different band-gaps covering the whole solar spectrum could successfully be made in a planer manner, which would be of interest for integrating with ARW. As shown in figure 1, the multi-striped solar cell structure is to be placed at the edges of ARW. The waveguide-coupled MOP³SC serves as a concentration photovoltaic system typically operating under a few hundreds to a thousand suns depending on the ARW size. Note that when the ARW's front layer that the incoming 3D sunlight encounters first is a sheet with an integrated parabola cross-section [9] we can regard all the incoming photons virtually impinge the periodic parabola mirrors at a right angle.

3. CUSP, a platform for processing MOP³SC and for obtaining big data

For processing the MOP³SC, clean unit system platform (CUSP) [2] which was, originally, developed for uniting bottom-up and top-down systems [11] are well suited, since CUSP, having fan-filter-unit (FFU) in full feedback configuration, is fully capable of providing us with highly clean space, no matter how dusty its ambient is. Dust- and microbe-free environment as good as US FED 209D class 1 ~100 is obtained with tent-type CUSP (T-CUSP). Sleeping in T-CUSP has made Kinetosomnogram (KSG) possible [12]. Based on the analysis of the peaks in the particle-count as well as its autocorrelation, KSG can evaluate body-movements of people in sleep. We have made it possible to extract useful information on the sleep quality from the time-dependence of the particle count and its autocorrelation.

Speaking of usage of net or tent-like structure, Japan has a long tradition of “*Kaya*” a net to prevent mosquitos from getting close while people is sleeping especially for summer. We have expanded the concept of *Kaya* by replacing the target, i.e., mosquitos by particles/dusts, and developed the tent type CUSP (T-CUSP) as shown in figure 3(a). People can sleep inside T-CUSP as usual with futon or mattress.

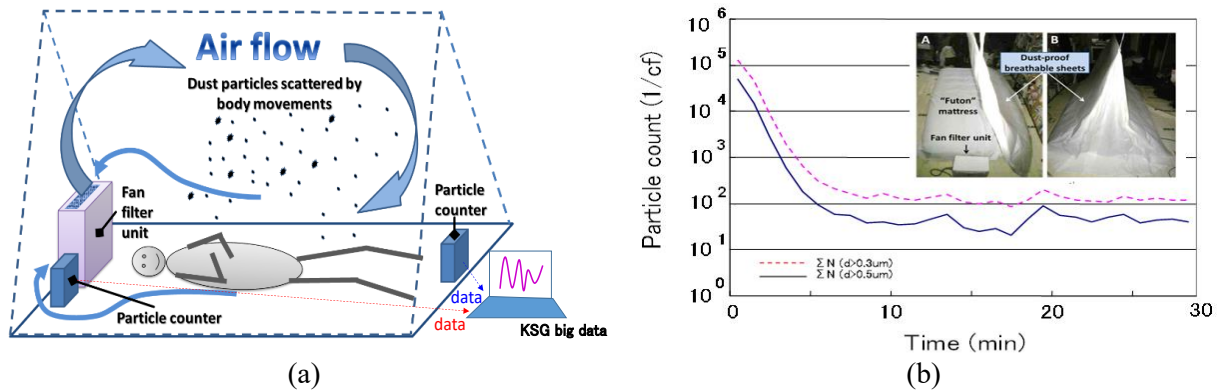


Figure 3. Cleanliness of T-CUSP (a) and Cleanliness of T-CUSP (b).

The particle (dust) density $n(t)$ in T-CUSP shown in figure 3(a) is governed by the equation,

$$\begin{aligned} V \frac{dn(t)}{dt} &= S\sigma - n(t)F + n(t)F(1 - \gamma) \\ &= S\sigma - \gamma Fn(t), \end{aligned} \quad (1)$$

where V and S , σ , and N_0 are, respectively, the volume of the closed space defined by the tent and futon placed on the floor, area of the inner surface of the closed space, rate of particles coming from the unit area (of the inner surface of the closed space) per unit time, and the particle density of the ambient space where the tent is placed. F is the flow rate of the fan filter unit set in the closed space, and γ is the filtrating efficiency of the FFU.

Equation (1) can be solved exactly quite easily [11] but what we are interested in is the steady-state

particle count, n , being obtained just by putting LHS of equation (1) i.e., $dn/dt = 0$, and it is given by

$$n = \frac{S\sigma}{\gamma F} \quad (2)$$

This is the dust density obtained as time goes by in CUSP. The T-CUSP size is compact, i.e., just enough to cover futon/mattress, which makes the volume of the closed space or the T-CUSP small and, as seen from equation (1), the conversion time scales with V/F , and low particle state is established quickly when V is small. The flow rate F of the FFU used in T-CUSP is typically about 1 cubic meters per minute and T-CUSP is 2 m long, 1m wide, and 1m high, giving $V \sim 2 \text{ m} \times 1 \text{ m} \times 1 \text{ m} / 2 \sim 1 \text{ m}^3$. The cleanliness provided is shown in figure 3(b). The solid line shows the number per cubic feet of particles whose size is 0.5 μm or larger. The cleanliness reaches class 100 in 5 minutes. Note that super cleanrooms have been used almost exclusively for semiconductor device processing, and it would be ridiculous to even try to sleep in super cleanroom with ordinary bedclothes. With T-CUSP, however, it has become quite affordable to sleep in such clean-space. Users can enjoy non-invasive, non-contact natural sleeping in very clean air, being free from nuisance of using a mask, under lower risk of suffering from PM2.5 [13,14] and/or diseases mediated by airborne microbes.

As seen in figure 3(b), in T-CUSP the air quality is improved from 50000-150000/cubic feet (cf) to 1-100/cf in 5 minutes for sum of the particles whose diameter is 0.5 μm or larger. A bout of body rolling in T-CUSP causes a surge of the air-borne particles with a peak of 3000-10000/cf in a minute (top figure in figure 4), and raising an arm or a leg does the same with a peak of 1000-2000/cf. These data suggest that the T-CUSP is suitable for assessing bio-kinetic signals in relation to body movements during sleep. Each surge of particle counts in the KSG appears to have a corresponding arousal response (stage W) in the hypnogram obtained by PSG as shown in figure 4. Moreover, there is a significant peak of power spectral density at 80-100 minutes suggesting of REM periods.

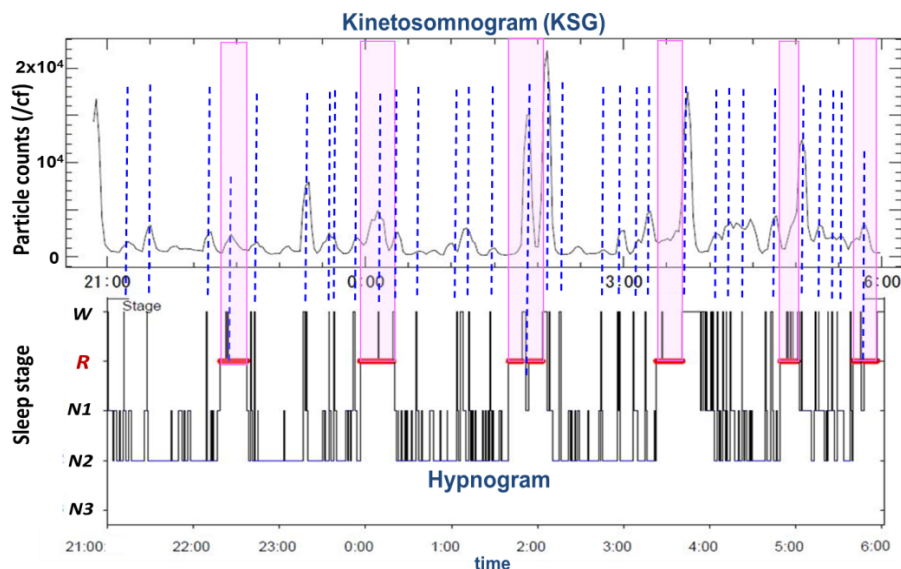


Figure 4. Comparison between kinetosomnogram (KSG) and hypnogram obtained by PSG.

Now let us denote those data that are human-related and of consciousness, respectively, as $(\uparrow, \uparrow)$. Point of sales (POS) is an example in this category. In this definition, internet of things (IOT) data, being of things and therefore not human-related and of no consciousness, are characterized by $(\downarrow, \downarrow)$. Then the aforementioned KSG produces the data having the property of $(\uparrow, \downarrow)$, since the data are of human and of no consciousness when they are asleep. Usually it is hard to connect data characterized

by $(\uparrow, \uparrow)$ and those characterized by $(\downarrow, \downarrow)$. When we are with data of $(\uparrow, \downarrow)$, however, situations changes. By coupling KSG data with existing data we can generating the data base with the features of $(\uparrow, \uparrow)(\uparrow, \downarrow)(\downarrow, \downarrow)$, a new data set with which we can handle the data on the Earth in brain-related, body-related, and IOT-related, highly sophisticated manner with no flips in the direction of the arrows across the data boundary (parentheses). Further, for detecting γ rays, a very sensitive detector called γ I has been developed [15]. Thus, when fan-filter-unit with a thick sheath is installed, CUSP can help people, together with γ I not to inhale dusts and particles containing ^{137}Cs or other radioactive elements by providing them with the clean air to live in. CUSP in its full line-up will be the cleanroom for all of us.

4. Conclusion

In ABE² space we have discussed a high efficiency solar cell and the processing platform of it, CUSP, and application of CUSP. We have investigated InGaN-based multi-striped orthogonal photon-photocarrier propagation solar cell (MOP³SC) in which the photons propagate in the direction orthogonal to that of the photocarriers. Because of the orthogonality, in the newly proposed solar cell, the absorption of light and the photo-carrier collection can be independently and simultaneously optimized without any trade-off. Furthermore, 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 solar spectrum into electricity resulting in the high conversion efficiency. When this multi-In striped structure is coupled to a waveguide, the further advancement can be expected. Not only the waveguide-coupled MOP³SC can optimize the absorption of light and the photocarrier collection independently and convert virtually the whole spectrum of sunlight into electricity, but also the waveguide-coupled MOP³SC is expected to serve as a highly efficient concentration photovoltaic system thanks to the low temperature rise (due to the minimal thermal dissipation) and the diffusive light convertibility when used, for example, with the integrated-paraboloid-sheet on the top of the waveguide. The waveguide-coupled MOP³SC 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 InGaN layer with less Indium content, never go into the medium or narrow gap semiconductors. Thus, the waveguide-coupled MOP³SC would serve as an ultimate high efficiency all-in-one system.

For processing MOP³SC, we have developed Clean Unit System Platform (CUSP), which turns out to be able to serve as clean versatile environment having low power-consumption and high cost-performance, and is suitable not only for processing devices, but also for cross-disciplinary fields, including medical/hygienic applications. CUSP can provide us with dust- and microbe-free environment as good as US FED 209E class 10 to 100 in foldable tent-type CUSP (T-CUSP). Sleeping in T-CUSP has opened a window for *Kinetosomnogram*, which, based on the analysis of the peaks in the particle-counts and the autocorrelation of them, would contribute to evaluation of sleep quality and/or sleep disorders. The T-CUSP can reduce the risk of diseases mediated by air-borne microbes as well as the risk of suffering from particulate matters (PM) 2.5 or other foreign materials. We envisage that CUSP would work as a proactive contributor of well-being. Breathing in this pristine air quality of CUSP, while sleeping for example, people would benefit from positive and direct effects to better health in the era of big data. The CUSP would be the clean space for all of us.

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