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Original Article

Photovoltaic potential of III-nitride based tandem solar cells

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ABSTRACT

In this work, we perform a detailed balance analysis of the maximum conversion efficiency of solar cells made from III-nitride materials. First, we present an analysis of single junction solar cells made from $In_xGa_{1-x}N$ alloys, and next we focus on tandem cells made from III-nitride and silicon materials. The performed simulations show that the two sub-cells system $In_{0.33}Ga_{0.67}N$/Si may present 42.43% maximum conversion efficiency, and the three sub-cells system $In_{0.33}Ga_{0.67}N$/Si/InN 47.83% efficiency under one-sun conditions.

1. Introduction

Photovoltaics is, by far, the most active sector of renewable energies with a worldwide increased by a factor of nearly 68 between 2000 and 2013 [1]. The largest part of photovoltaic modules are made of silicon solar cells. Theoretically, the maximum conversion efficiency of silicon cells is about 30% under one-sun conditions. This theoretical limit is, almost, reached with ongoing technology improvements. Indeed, more than 25% efficiency has been achieved by laboratory heterojunction cells [2,3]. To further increase this theoretical limit, there are several advanced concepts of solar cells [4] known as next or third generation photovoltaic cells. Among these concepts, tandem cells made from two or more sub-cells with different bandgaps, represent the most successful concept until now.

III-nitride (GaN, AlN, InN) semiconductors and their alloys are widely used materials in optoelectronics to fabricate green, blue and UV LEDs and lasers. Since the main technological difficulties facing this branch of semiconductor materials have been overcome (i.e. p type doping [5], Ohmic contact formation [6] and MOCVD hetero-epitaxy of III-nitrides [7]), the development of solar cells based on these materials is becoming possible.

From a photovoltaic point of view, since these materials have bandgaps ranging from 0.7 eV for InN to 3.4 eV for GaN up to 6.2 eV for AlN [8], these materials are potential candidates for manufacturing tandem solar cells with high conversion efficiency. Nevertheless, to our knowledge, few successful research works [9] have been done on photovoltaic applications of these materials.

2. Theory and simulation

The well-known detailed balance principle was used in 1961 by Shockely and Queisser [10] for the calculation of the maximum efficiency of single pn junction solar cells. From this principle, the maximum current that may be delivered by a single junction solar cell under any applied voltage U is the difference between the generated current by solar radiation (black-body radiation under $T_{sun} = 6000$ K which, roughly, corresponds to AM0 standard radiation) and the recombination current:

$$J(U) = J_{gen} - J_{rec}(U) \tag{1}$$

Here all carrier recombination is supposed to be radiative, and the solar cell radiation is taken as exponentially increased black-body radiation at $T_{cell} = 300$ K. Charge carrier mobility is supposed to be infinite and no parasitic resistances are assumed. Under these assumptions the delivered current can be written as follows [4]:

$$J(U) = qf_s\dot{N}(Eg,\infty,0,T_{sun}) + q(f_c - f_s)\dot{N}(Eg,\infty,0,T_{cell}) - qf_c\dot{N}(Eg,\infty,qU,T_{cell}) \tag{2}$$

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Here $\dot{N}(E_i, E_f, \mu, T) = \frac{2\pi}{h^3c^2}\int_{E_i}^{E_f}\frac{E^2}{e^{\frac{E-\mu}{kT}}}dE$ is the blackbody photon flux per unit of surface area from E_i to E_f at temperature T, q is the elementary charge, h and k are Planck's and Boltzmann's constants, respectively, c is the light velocity in vacuum, Eg is the cell material bandgap energy, and μ (eV) is the chemical potential, which represents the quasi-Fermi level separation.

The factor $f_s = 2{\cdot}16\ 10^{-5}$ represents the fraction of solar radiation attaining earth's surface and is equals to 1 under maximum concentration, and the factor f_c is taken equal to 1 to represent the whole solar cell area.

For example, calculated J(U) and P(U) (the output power) characteristics of a silicon cell (for Eg = 1.1 eV) are shown in Fig. 1.

Fig. 1 shows that the short circuit current J_{SC}, the open-circuit voltage V_{OC}, and maximum delivered power P_m of a silicon cell are 62 mA/cm^2, 0.88 V and 48.1 mW/cm^2, respectively.

Then, the solar cell conversion efficiency η can be calculated using equation (3)

$$\eta\ (\%) = \frac{P_m(W/m^2)}{X \cdot P_{in}(W/m^2)} \cdot 100 \tag{3}$$

The factor X is equal to 1 for one-sun radiation and 46200 for full (maximum) concentration, and P_{in} = 1584 W/m^2 is incident blackbody power per unit area.

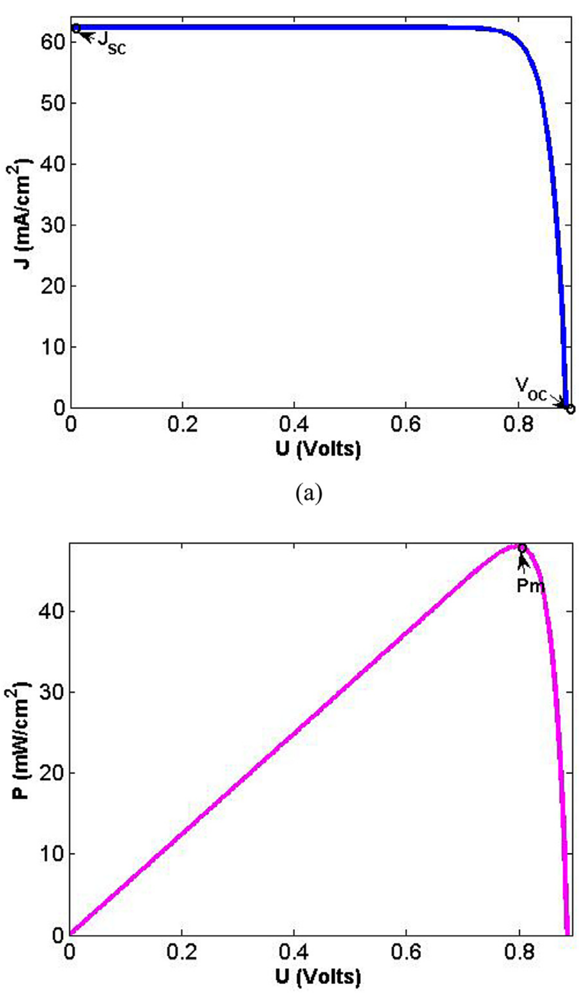

Fig. 1. J(U) characteristics (a) and P(U) characteristics (b) of silicon single junction solar cells.

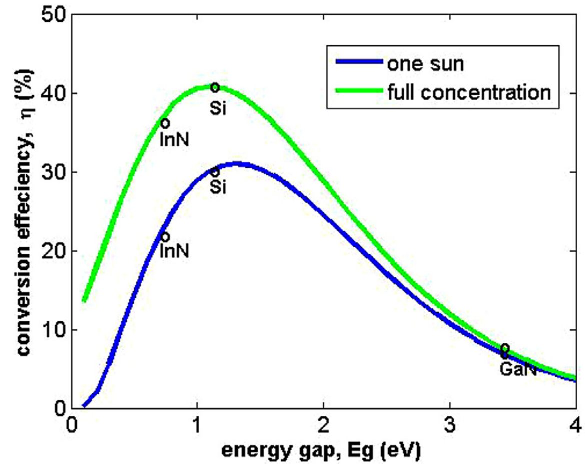

Fig. 2. Maximum conversion efficiency of single junction solar cells versus bandgap under one sun and full concentration conditions.

Fig. 2 shows the maximum conversion efficiency of single junction solar cells as a function of the material bandgap. From this figure one can see that the maximum conversion efficiency of single junction cells at one sun is about 31% for a gap energy of 1.3 eV.

One of the most promising concepts to overcome this limit is to make use of tandem solar cells containing more than one sub-cell with different energy bandgaps. Each one of these sub-cells absorbs a part of solar spectrum, resulting in a higher conversion efficiency. Building tandem cells may be done in two different manners, either by (i) splitting the solar spectrum using perfect wavelength-selective mirrors to match each sub-cell bandgap, or by (ii) stacking the sub-cells in one a two terminal multi-junction cell where the largest bandgap sub-cell comes on top followed by the second largest bandgap one and so on.

In the following section we will focus on the first kind of tandem cells, in which each cell is independently biased to reach its optimum operating point, see Fig. 3. In this case, we do not need to consider the emitted light absorbed by other sub-cells.

We also suppose perfect mirrors without absorption losses. Under these assumptions, the delivered current by each cell of bandgap Eg_n under the appropriate voltage U_n, resulting in maximum delivered power, is given by the following equation [4]

$$\begin{aligned} J_n(U) = {} & qf_s\dot{N}(Eg_n, Eg_{n+1}, 0, T_{sun}) \\ & + q(f_c - f_s)\dot{N}(Eg_n, Eg_{n+1}, 0, T_{cell}) \\ & - qf_c\dot{N}(Eg_n, Eg_{n+1}, qU_n, T_{cell}), \end{aligned} \tag{4}$$

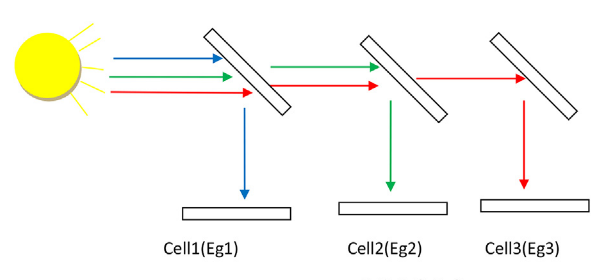

Fig. 3. Tandem solar cell principle using spectrum splitting.

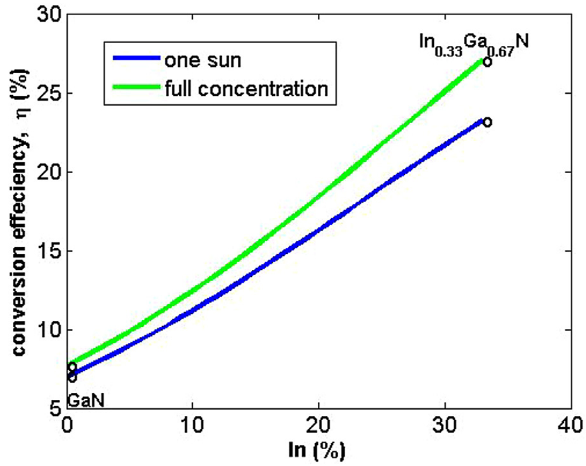

Fig. 4. Maximum conversion efficiency of single junction $In_xGa_{1-x}N$ solar cells versus indium content.

where Eg_{n+1} is the bandgap of next highest bandgap cell. To calculate the conversion efficiency, the delivered power is taken as the sum of delivered powers by each sub-cell.

3. Results and discussion

3.1. Single junction InGaN cells

After Vegard's law, the bandgap of $In_xGa_{1-x}N$ alloys may be calculated from InN and GaN gaps as following

$$Eg(In_xGa_{1-x}N) = xEg(InN) + (1-x)Eg(GaN) - bx(1-x), \quad (5)$$

where b is bowing factor here equal to 1.916 [11].

Fig. 4 shows the maximum conversion efficiencies of single junction $In_xGa_{1-x}N$ cells under one-sun and full concentration conditions versus Indium content for $0 \le x \le 0.33$. Indium content in InGaN alloys cannot exceed 33% due to phase separation [8].

3.2. Tandem cells

Since in the spectrum splitting configuration, Fig. 3, we do not have to consider lattice matching like in multi-junction configuration, we are free to choose any combination of sub-cells to reach the maximum conversion efficiency. In the next subsections, we will consider tandem cells containing two and then three III-nitride sub-cells.

3.2.1. Two sub-cell systems

The highest efficiency that can be obtained using two sub-cells is 42.86% for sub-cells energy gaps $Eg_1 = 1.87$ eV and $Eg_2 = 0.98$ eV under one sun conditions [12]. In Table 1 examples of calculated maximum efficiencies for some bandgap combinations are given.

Table 1
Calculated maximum conversion efficiencies of two sub-cells tandem solar cells based on III-nitride materials.

Sub-cell1/Sub-cell2	Eg_1/Eg_2 (eV)	η (%)
GaN/InN	3.4/0.7	27.79
GaN/Si	3.4/1.1	35.15
Si/InN	1.1/0.7	35.44
$In_{0.33}Ga_{0.67}N$/Si	2.09/1.1	42.43

Table 2
Calculated maximum conversion efficiencies of three sub-cells tandem solar cells based on III-nitride materials.

Sub-cell1/Sub-cell2/Sub-cell3	$Eg_1/Eg_2/Eg_3$ (eV)	η (%)
$In_{0.33}Ga_{0.67}N$/Si/InN	2.09/1.1/0.7	47.83
$In_{0.28}Ga_{0.72}N$/Si/InN	2.26/1.1/0.7	47.28
GaN/Si/InN	3.4/1.1/0.7	40.56
GaN/$In_{0.33}Ga_{0.67}N$/InN	3.4/2.09/0.7	42.07

By comparing these results to single junction efficiency, one can remark that the combination of silicon sub-cell with III-Nitride sub-cells gives greater efficiencies, and the best choice is the $In_{0.33}Ga_{0.67}N$/Si system, Table 1.

3.2.2. Three sub-cells systems

As is already shown in the literature [12,13], the highest conversion efficiency of three sub-cell systems under one-sun conditions is 49.26% for sub-cell energy gaps $Eg_1 = 2.26$ eV, $Eg_2 = 1.44$ eV and $Eg_3 = 0.82$ eV . We find that one can obtain a high efficiency of 47.83% using $In_{0.33}Ga_{0.67}N/Si/InN$ system of sub-cells (Table 2).

4. Conclusion

We have presented a detailed balance calculation of maximum conversion efficiency of III-nitride material based solar cells. Since the indium content of $In_xGa_{1-x}N$ alloys cannot exceed 33%, the conversion efficiency of single junction InGaN cells cannot exceed 28%. On the other hand, we have found that efficiencies of more than 40% may be achieved by introducing a silicon sub-cell in tandem cell configurations. The two sub-cell $In_{0.33}Ga_{0.67}N$/Si system presents an efficiency of 42.43% and the three sub-cell $In_{0.33}Ga_{0.67}N$/Si/InN system gives 47.83% efficiency under one-sun radiation.

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