The characterization of p-GaAs/i-InGaAsN/n-GaAs hetero-junction solar cell with various DMHy flow rates

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Abstract

Since the high efficiency tandem solar cell structure has been reported, the conversion efficiency of triple-junction solar cells could achieve 40% with concentrator [1]. To further enhance the conversion efficiency of solar cells, the fourth-junction is used to decrease the wasting of energy transformation caused by current limiting in tandem solar cells, so that the conversion efficiency of four junction tandem solar cell is expected to achieve up to 45%. Thus, InGaP/GaAs/ InGaAsN/Ge (1.8/ 1.42/ ~1/ 0.7eV) hetero-structures have attracted much attention [2,3] recently. In this study, we tried to optimize the device structure by reducing the N content to 2.8% in the InGaAsN absorption layer. However, we decreased the nitrogen composition from 3.3% to 2.8% by reducing the DMHy/V_T ratio, and the 600 nm thick InGaAsN absorption layer is lattice-match to GaAs substrate. Thus, the short-circuit current density could also be considerably increased to 14.8 mA/cm^2.without antireflection coating layer. Therefore, the conversion efficiency could be improved to 2.94%.

Keywords: solar cells, dilute nitride, 1 eV material, InGaAsN, fourth junction

Introduction

Silicon (Si) single-crystal and poly-crystalline homojunction cells with which the electronics industry feels most at home dominate the photovoltaic market, largely due to the large area, relatively inexpensive substrates. However, Si is a poor choice of material with 1.12 eV indirect bandgap for maximizing efficiency because of fundamental limits [4], it means that unsophisticated cells must be at least hundreds of micrometers thick to absorb all the active wavelengths in sunlight with reasonable efficiency. By contrast, III-V semiconductor such as gallium arsenide (GaAs) with 1.42 eV direct bandgap and related alloys can effectively absorb sunlight with only a few micrometers, such optical property allows III-V solar cells to be made much thinner. Although III-V solar cells must to be grown on expensive substrates by advanced deposition technique, III-V alloys still have several significantly advantages. One is that for GaAs-based materials, these semiconductors are valued in the optoelectronics for the high hole mobility of the n-type material, so III-V compounds are much more efficient in converting the Sun's radiation into electricity. Another is the possibility of varying composition by replacing some of the group III atoms with another group-III element in order to vary the bandgap in a controlled way by metal-organic vapor phase epitaxy (MOVPE) or molecular beam epitaxy (MBE). Then, it can lower surface recombination in III-V solar cells by adding window layer and back surface field (BSF) into the cell structure. Last, III-V solar cells reveals the better radiation resistance than Si solar cells exhibit a rather low tolerance of solar concentration at several hundred times above normal [5].

The high-efficiency InGaP/GaAs/Ge monolithic three-junction solar cell is applied for space applications and is a leading candidate for terrestrial high-concentration solar cells due to its record-setting efficiency. However, the Ge bandgap is not optimal for the third junction because there are large differences of energy gap between GaAs and Ge. The next-generation of three- and four-junction devices using appropriate bandgap materials is projected to have significantly higher efficiencies if the third junction could be fabricated from a 1 eV band gap material. The theoretical conversion efficiencies of an idealized InGaP/GaAs/1-eV/Ge four- junction structure are predicted to exceed 40% and even 50% for the AM 0 and AM 1.5D at 500 suns conditions, respectively [6]. As mentioned above, it will require a set of III-V materials with near 1 eV bandgap, preferably lattice matched to GaAs to minimize strain-induced defects that severely degrade solar cell performance.

Experiment

In this study, we have grown the *p*-GaAs/*i*-InGaAsN/*n*-GaAs double heterojunction solar cell (DHJSC) by AIX200 metalorganic chemical vapor deposition (MOCVD) system. $In_xGa_{1-x}As_{1-y}N_y$ films were grown by using the trimethyl-indium (TMIn), trimethylgallium (TMGa), ter-tiarybutylarsine (TBAs), and dimethyl-hydrazine (DMHy) as the precursor. InGaAsN DHJSCs were grown on *n*-type GaAs substrate orientated 2^o off (100) towards <110>. The lattice-matched InGaAsN epi-layers were grown at the growth temperature of 550^{o}C with DMHy flow rate of 3.5×10^{-3} mol/min and 3.8×10^{-3} mol/min, respectively. We have optimized the parameters to grow intrinsic InGaAsN absorption layers at 550^{o}C of double hetero-junction *p-i-n* solar cell[4]. All of the solar cell structures consist of a 30 nm-thick p^+-$Al_{0.3}Ga_{0.7}As$ window layer, 300 nm-thick n^+-$Al_{0.3}Ga_{0.7}As$ back surface field layer, and GaAs capping layer; the growth temperature ranged from 675 to 725 ^{o}C.. No antireflection coatings (ARCs) were used. Solar cells were processed with an area of 0.0625 cm^2. The cell devices manufacture procedure is shown as follows, solar cell samples are put in acetone, isopropyl alcohol, DI water, ammonia solution (NH_4OH) and DI water for 5 minutes in turn to oxidize organic films and remove native oxides. Then, the upper contact is defined by the first photolithography using negative photoresist, follow by the AuZn (95/5 wt%) alloy deposition of thickness about 190 nm by means of thermal evaporation and lift-off technique is used to remove the metal outside the defined area. Next, the second photolithography also using negative photoresist is carefully aligned to protect the p-contact metal and the cell chip definition step is to separate the cell chip to each other and allows the individual measurement by utilizing an etching solution of H_2SO_4, H_2O_2 and DI water (1 : 3 : 46). Subsequently, the n-side contact is formed by AuGeNi (84/12/4 wt%) alloy on the GaAs substrate by means of thermal evaporation. Finally, both contacts are annealed at 420°C for 3 minutes in N_2 ambiance by an annealing furnace and the p$^+$-GaAs cap layer was removed away to reduce the absorption of light in the cap layer by using an etching solution of NH_4OH, H_2O_2 and DI water (1 : 1 : 100). The schematic illustration of the solar cell structure was shown in Fig. 1.

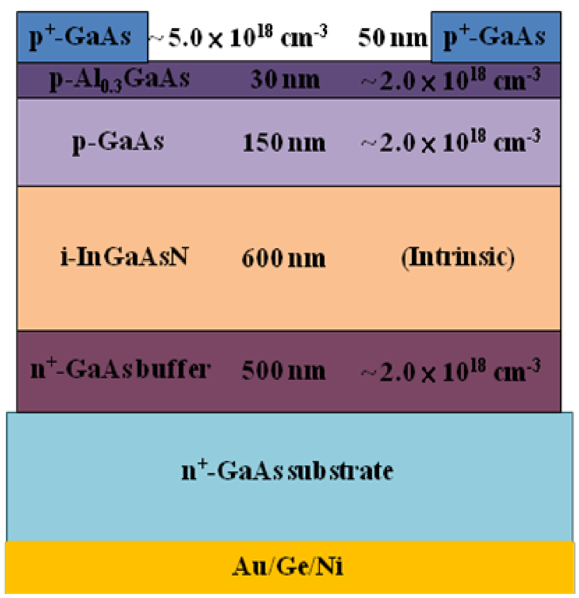

Fig. 1:Schematic illustration of the InGaAsN DHJSC structure. (not to scale)

Result and discussion

Incorporating nitrogen into InGaAs would reduce its bandgap with the nitrogen penalty effect of drastic degrading optical properties [8-9] due to the poor crystal quality, compositional inhomogeneity and the generation of

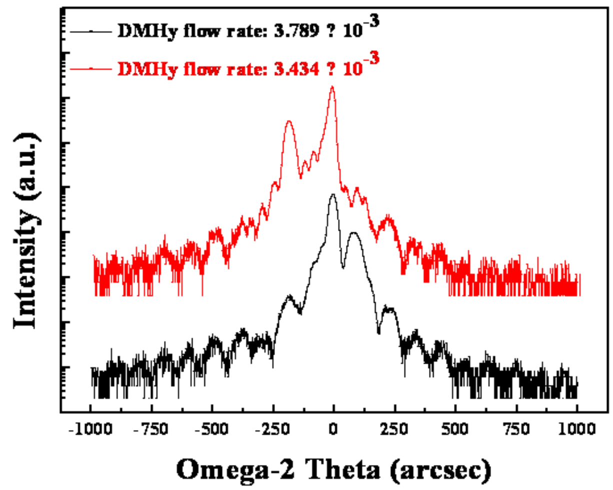

Figure 2: X-ray rocking curves of InGaAsN DHJSCs with various DMHy flow rates.

non-radiative recombination centers accompanied by the incorporation process of nitrogen and its low growth temperature [10-12]. Therefore, we decided to decrease the DMHy flow rate to lower the nitrogen incorporation in the InGaAsN absorption layer. Figure 2 shows the x-ray diffraction rocking curve of the InGaAsN DHJSCs with various DMHy flow rates. As shown in table 1, compared to the InGaAsN layer with higher DMHy flow rate resulted in a

DMHy flow rate (mol/min)	lattice mis-match (ppm)	N content (%)
3.789×10^{-3}	-331.1	3.3
3.434×10^{-3}	706.1	2.8

Table 1: The relative parameters of InGaAsN DHJSCs from XRD rocking curves

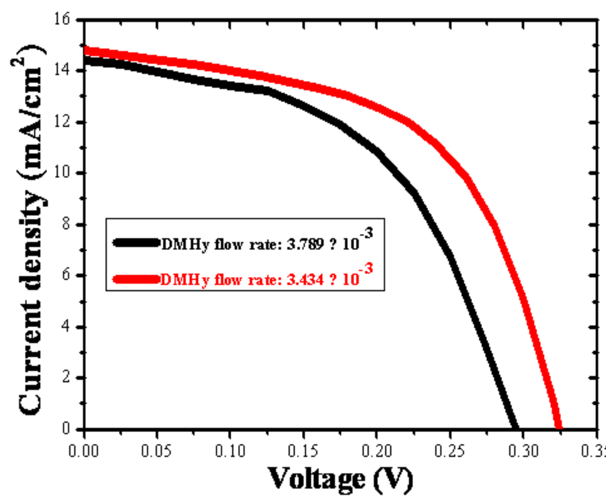

Figure 3. *I-V* characteristics of InGaAsN DHJSCs with various DMHy flow rates under AM 1.5G illumination.

-331.1 ppm lattice-mismatch, the DMHy flow rate must be fine-tuned from 3.789 × 10^{-3} mol/min to 3.434 × 10^{-3} mol/min, thus the lattice-mismatch between the InGaAsN layer and GaAs substrate could be controlled within 800 ppm. It can be observed that not only the nitrogen content decreased from 3.3% to 2.8% obviously, the lattice-mismatch was also controlled at about 706.1 ppm. Then, the measured J-V characteristics of the DHJSCs under AM 1.5G illumination was shown in Fig. 3 and revealed a significant improvement in the short-circuit current density from 11.56 mA/cm^2 to 15.59 mA/cm^2 due to the nitrogen penalty effect reduction. In addition, the open-voltage and fill factor were found to be independent of the nitrogen incorporation mechanism based on the same device structure. As a result, the conversion efficiency can be increased from 1.79% to 2.47% (see Table 2).

DMHy flow rate (mol/min)	V_{oc} (V)	J_{sc} (mA/cm^2)	η (%)
3.789 × 10^{-3}	0.295	14.2	2.39
3.434 × 10^{-3}	0.324	14.8	2.94

Table 2: Conversion efficiency and relative parameters of InGaAsN DHJSCs with various DMHy flow rates

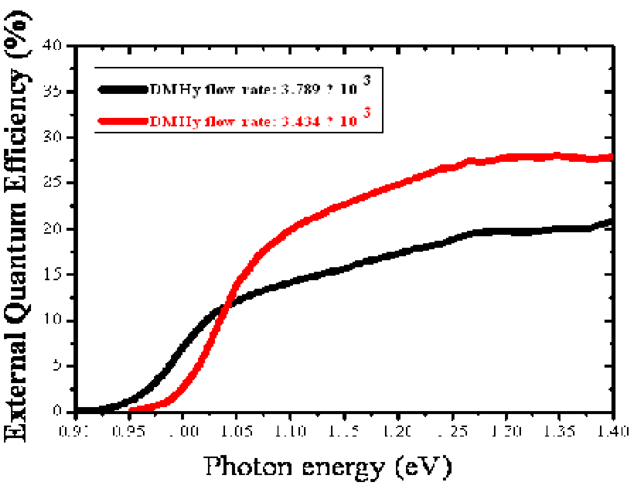

Figure 4: Comparison of quantum efficiency between InGaAsN DHJSCs with various DMHy flow rates.

Figure 4 reveals the external quantum efficiency of DHJSCs with various DMHy flow rates. From Fig. 4 we could observed the DHJSCs with lower DMHy flow rate tended to absorb shorter wavelength incident light, the absorption wavelength region was about 1200 nm. The external quantum efficiency of high DMHy flow rate DHJSC is lower than of lower DMHy flow rate in short wavelength region (the photon energy is ranging from 1.1 to 1.4 eV). This implied that the nitrogen incorporation could lead to nitrogen induced defects or dislocation and deteriorated the characteristics of InGaAsN absorption layer and as a result the DHJSC with higher DMHy flow rate reached lower spectral response in the short wavelength region.

Conclusion

In this study, we have optimized the device structure to enhancing the solar cell with 1eV material absorption layer conversion efficiency. By lowering the N content to 2.8% in the InGaAsN layer, the defects of InGaAsN absorption layer induced by N cluster would decrease. On the other hand, when we decreased the nitrogen composition from 3.3% to 2.8% by reducing the DMHy/V_T ratio, the InGaAsN absorption layer with 600 nm thickness is lattice-match to GaAs and the short-circuit current density could also be considerably increased to 14.8 mA/cm^2 with a relative enhancement of 4.2%. Therefore, the conversion efficiency could be improved to 2.94%, though the absorption region would shrink with higher DMHy flow rate.

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