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PERFORMACE OF DILUTE NITRIDE TRIPLE JUNCTION SPACE SOLAR CELL GROWN BY MBE

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ABSTRACT

Dilute nitride arsenide antimonide compounds offer widely tailorable band-gaps, ranging from 0.8 eV to 1.4 eV, for the development of lattice-matched multijunction solar cells with three or more junctions. Here we report on the performance of GaInP/GaAs/GaInNAsSb solar cell grown by molecular beam epitaxy. An efficiency of 27% under AM0 conditions is demonstrated. In addition, the cell was measured at different temperatures. The short circuit current density exhibited a temperature coefficient of 0.006 mA/cm^2/°C while the corresponding slope for the open circuit voltage was -6.8 mV/°C. Further efficiency improvement, up to 32%, is projected by better current balancing and structural optimization.

1. INTRODUCTION

Commercial space solar cells have reached 30% beginning of life (BOL) efficiencies [1]. For even higher efficiencies and more efficient spectral utilization, the development of new materials is needed. In lattice matched GaInP/GaInAs/Ge cell the spectral range from 0.7 eV to 1.4 eV is covered by the Ge sub-junction. In this case, there is a high overall quantum defect between photon energies and the band-gap energy of Ge leading to inefficient energy conversion. Consequently, Ge junction is generating approximately only 0.2 V. Lattice matched 1 eV band-gap dilute nitrides, such as GaInNAsSb alloys, offer lower quantum defect and higher voltage generation. The best band-gap voltage offset value demonstrated for dilute nitride junction is 0.49 V [2]. Therefore, with current balanced ~1 eV dilute nitride junction, up to 0.3 V higher operation voltage could be produced than with Ge junction. Projective calculations based on diode modelling and the measured performance of dilute nitride cells have shown that for realistic GaInP/GaAs/GaInNAsSb design, the BOL efficiency could increase approximately 3 percentage points when compared to a Ge-based cell [3]. Moreover, the incorporation of dilute nitrides in a four junction cell with Ge bottom junction could give additional 2 percentage points higher efficiency, yielding ultimately 35% BOL efficiency [3]. Here we demonstrate a triple junction GaInP/GaAs/GaInNAsSb solar cell grown by molecular beam epitaxy (MBE), which sets a roadmap towards demonstrating higher efficiencies and solar cells incorporating higher number of junctions.

2. EXPERIMENTS

The GaInP/GaAs/GaInNAsSb solar cell structure was grown monolithically on p-GaAs substrate using a Veeco GEN20 MBE-system. Detailed description for the fabrication process can be found elsewhere [4, 5]. Subsequent to the growth, the wafer was processed into 4x4 mm^2 solar cells. TiAu and NiAu alloys were used for p- and n-side contacts, respectively. For anti-reflection coating, we used a double-layer TiO_x/SiO_x thin film [6]. For the measurements, we used a spectrally adjustable in-house built three-band solar simulator, which was set to AM0 spectral conditions with separately calibrated single junction GaInP, GaAs and GaInNAsSb cells. ASTM E490 AM0 spectrum (1366 W/m^2) [7] was used for reference. External quantum efficiency (EQE) measurements were performed using an in-house built, monochromator based, measurement system. In addition, for different spectral regions, proper set of band pass filters were used, which ensures monochromatic probe beam. The EQE system response was calibrated with Si and Ge detectors. For the performance analysis and performance projections we used diode modelling employing the parametrization described earlier [3, 8].

3. RESULTS AND DISCUSSION

The current-voltage (*I-V*) performance of the GaInP/GaAs/GaInNAsSb cell illuminated with AM0 three band solar simulator is shown in Fig. 1a. The short circuit current density (J_{sc}) was 17.2 mA/cm^2. Our analysis concluded that the cell was current limited by the GaInP top cell. The open circuit voltage (V_{oc}) and fill factor (*FF*) were 2.67 V and 80%, respectively. The band-gaps for GaInP/GaAs/GaInNAsSb cell are 1.9 eV, 1.4 eV and 0.98 eV, respectively. These values are revealed by the EQE measurement performed at 22°C, which is shown in Fig. 1b. In addition, Fig. 1b reveals the EQE measurement at 80°C. The J_{sc} for the sub-junctions calculated using the EQE measurements are presented in the Tab. 1. For the GaAs sub-junction, the limiting current was estimated from both EQE and using a three band solar simulator measurements to give realistic values. For GaInP top cell and for GaInNAsSb bottom cell the values were directly calculated from the EQE measurements and AM0 spectrum.

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Table 1. Analysis of the EQE measurements.

Sub-cell	Band-gap$_{22°C}$ (eV)	$J_{sc22°C}$ (mA/cm^2)	Band-gap$_{80°C}$ (eV)	$\Delta J_{sc(25 \rightarrow 80°C)}$ (mA/cm^2)
GaInP	1.88	17.1	1.85	+0.4
GaAs	1.41	17.7*	1.37	+0.4
GaInNAsSb	0.98	18.5	0.96	-0.2

*Limited EQE measurement performance for the GaAs sub-junction, J_{sc}-values are estimated for GaAs cell based on the EQE and solar simulator measurements.

For the absolute comparison and projective analysis of GaInP/GaAs/GaInNAsSb cell performance, diode modelled *I-V*-characteristics of a current matched cell are also presented in Fig. 1a. The comparison reveals that with further current matching and band-gap tuning, 4 percentage points higher efficiencies are projected for the optimized GaInP/GaAs/GaInNAsSb cell. For better current matching, structural optimization is needed for GaInP and GaAs sub-cells, which we have started with very promising results. Therefore, we believe that the J_{sc} can be increased at least to 17.7 mA/cm^2. The triple junction cell has 0.18 V lower V_{oc} than the simulated cell. This voltage drop can be reduced with band-gap engineering and material improvements.

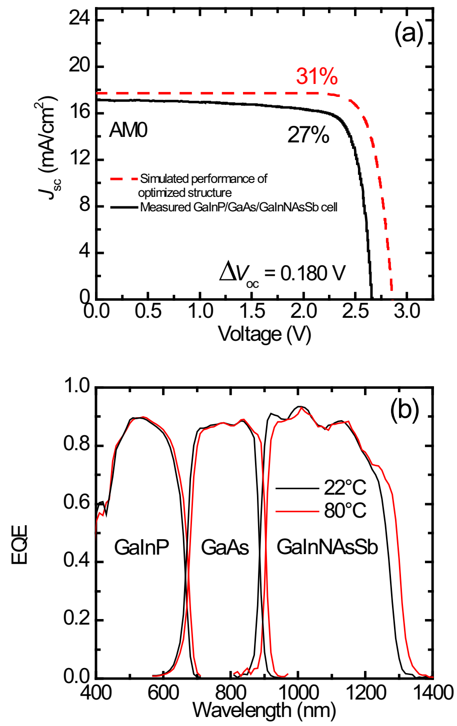

Figure 1. (a) AM0 biased IV-characteristics of GaInP/GaAs/GaInNAsSb solar cell and the simulated performance of GaInP/GaAs/GaInNAsSb cell. (b) EQE characteristics of GaInP/GaAs/GaInNAsSb solar cell measured at 22°C and 80°C.

Approximately 0.1 V higher V_{oc} can be obtained by using higher band-gap for the GaInNAsSb junction. For the remaining voltage gap of 0.08 V, structural and material quality optimizations are the key factors. Ultimately, additional 0.05-0.09 mV improvement for the GaInNAsSb sub-junction might be expected with optimization and improved design, yielding efficiency as high as 32% for the triple junction cell.

Moreover, the temperature coefficients for the cell were defined by the *I-V* measurements performed in the temperature range of 25-90°C. The relative change of the J_{sc} value for the GaInP/GaAs/GaInNAsSb cell is presented in Fig. 2a, while Fig. 2b shows the dependence on the cell V_{oc} as the function of the cell temperature. The J_{sc} temperature coefficient was 0.006 mA/cm^2/°C while the corresponding value for V_{oc} was -6.8 mV/°C. The J_{sc} temperature coefficient calculated from EQE was also 0.006 mA/cm^2.

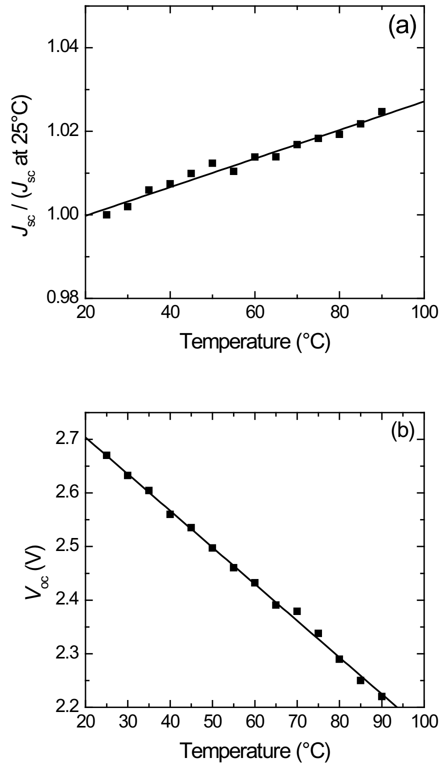

Figure 2. (a) Temperature dependent J_{sc} normalized to J_{sc} at 25°C. (b) Temperature dependence of V_{oc} for GaInP/GaAs/GaInNAsSb cell.

4. CONCLUCION AND FUTURE WORK

We have demonstrated a high performance GaInP/GaAs/GaInNAsSb space solar cell with an efficiency of 27% at AM0 conditions. Using realistic diode model simulation, we show that the efficiency of GaInP/GaAs/GaInNAsSb cell could reach 31%, following current matching and band-gap optimization of the dilute nitride bottom cell. Ultimately, with further optimization of the triple junction cell interfaces and material quality, an BOL efficiency as high as 32% is feasible. We also determined the temperature coefficients for J_{sc} and V_{oc}, which were 0.006 mA/cm^2/°C and -6.8 mV/°C, respectively.

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