Narrow Bandgap Dilute Nitride Materials for 6-junction Space Solar Cells

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***Abstract*—Narrow bandgap p-i-n dilute nitride GaInNAsSb junctions, for use as bottom cell in 6-junction solar cells, are reported. In particular, we demonstrate a high optical quality for GaInNAsSb junction with a bandgap ~0.78 eV, corresponding to a N content of 6.2%. Under AM0 illumination, such cell exhibits a photocurrent of 36.6 mA/cm^2. By extracting the parameters of the experimental cell, we estimate the the AM0 efficiency of a 6-junction multijunction solar cell employing the GaInNAsSb junction, to attain a value of 33%. Further improvements are discussed towards achieving the full potential of the 6-junction design.**

Keywords*—*dilute nitride, multijunction solar cell, molecular beam epitaxy, GaInNAsSb

I. Introduction

Lattice-matched GaInP/GaInAs/Ge triple-junction (3J) cells with 30% conversion efficiency at AM0 are commercially available [1]. Yet, solar cells with higher efficiencies are needed to be used in future space power systems. To this end, by increasing the number of junctions, higher efficiencies can be obtained. With a wafer bonded 5-junction (5J) solar cell, a conversion efficiency of 35.8% at AM0 has been demonstrated [2]. Monolithic 5J cells grown by metal-organic chemical vapor deposition (MOCVD) have also been reported [3,4] but their efficiency has not exceeded 3J cell performances. For better utilization of the solar spectrum, the use of a 6th junction with bandgap of 0.9–1.1 eV on top of the Ge-junction exploited in the 5J design has been proposed [4]. This junction could be made out of dilute nitride materials, i.e. GaInNAs(Sb), which can be grown lattice-matched to GaAs and Ge and with bandgaps ranging from 1.4 eV down to 0.7 eV [5]. Dilute nitrides grown by molecular beam epitaxy (MBE) with bandgaps around 1 eV have successfully been employed in high-efficiency MJSCs [6-8]. Moreover, dilute nitrides with bandgaps around 0.8 eV have been demonstrated [5,9] earlier, but their photovoltaic properties have remained generally modest. We have recently reported on the development of lattice-matched GaInNAsSb with high N compositions between 5% and 8% corresponding to bandgaps between 0.7 eV and 0.9 eV for high-efficiency concentrated photovoltaics [10]. Here we assess the use of our narrow bandgap GaInNAsSb materials for space solar cells. In particular, we discuss the external quantum efficiency (EQE) and light-biased current-voltage (LIV) performance of single junction solar cells made from these materials and evaluate their applicability for 6J space solar cells at AM0 conditions.

II. Experimental

The single junction GaInNAsSb p-i-n solar cells with N compositions of 5–8% were grown on n-GaAs(100) substrates using a Veeco GEN20 plasma-assisted MBE-system. The solar cell structures comprised 700 nm GaInNAsSb i-region between 100 nm of p-type and n-type GaAs layers with GaInP back surface field and window layers. The GaInNAsSb layers had a nominal In composition of 15% and the N composition of the layer was varied nominally between 5.2% and 8.3%. The actual In, Sb and N compositions of the GaInNAsSb layers were directly measured by EDS. A more detailed description of the sample structures, growth parameters and material characterization can be found in [10]. The wafers were processed into 6 mm × 6 mm solar cells without antireflection coatings (ARC). The LIV characteristics were measured using an OAI TriSol 7 kW CPV-simulator with AM0 excitation. The EQEs were measured using an in-house built monochromator based EQE setup equipped with an Oriel 250 W QTH lamp The EQE system was calibrated with reference Ge and Si detectors. The efficiency potential for the 6J design incorporating a dilute nitride junction with 0.78 eV bandgap for the bottom junction was evaluated by diode modelling using realistic parameters for the subcells.

III. Results and discussion

EQEs measured for the GaInNAsSb single junction cells are shown in Fig. 1. Cell with a N content of 6.2% (corresponding to E_g = 0.78 eV), exhibited the highest response, which is 3-5 times higher in the range of 1400-1600 nm than previously reported for a 0.77 eV GaInNAsSb cell [9]. Although the EQE response of the cell with 7.9% N concentration is relatively low, this material also results in a functional cell with a bandgap energy of 0.73 eV. In addition,

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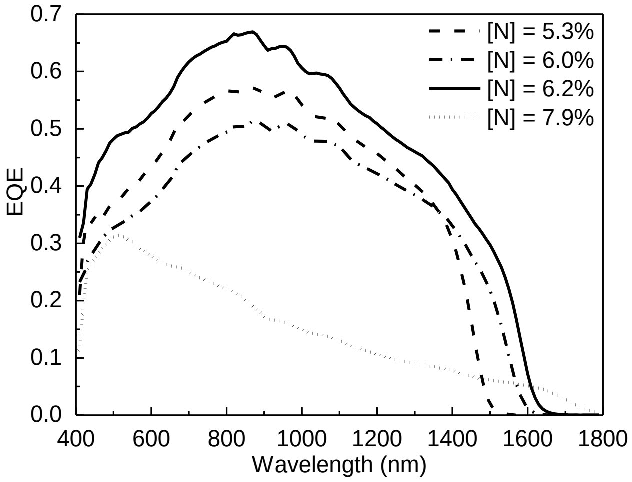

Fig. 1. Measured EQEs for GaInNAsSb single junction cells.

the EQE of the 0.73 eV cell already surpasses the EQE performance reported for the 0.77 eV GaInNAsSb cell [9].

The short-circuit current density (J_{sc}) estimated from the EQE for the cell with 6.2% N is 37.2 mA/cm^2, for full spectrum AM0 (ASTM E490) excitation. The EQE data for the 0.78 eV cell was used to estimate the current generation of such subcell in a multijunction architecture, where the light is filtered by an optically thick junction with varying bandgap energy. In addition, the effect of a 4-layer TiO_x-SiO_x ARC on current generation was estimated. The estimated short-circuit current densities for the cell with 6.2 % N are shown in Fig. 2.When incident light is filtered by a thick 1.1 eV junction, the J_{sc} of the GaInNAsSb junction is estimated to be 7.9 mA/cm^2. If a 4-layer TiO_x-SiO_x ARC would be applied on top of the solar cell, the J_{sc} at under spectrum AM0 excitation is estimated to be 50.9 mA/cm^2 and 10.2 mA/cm^2 below a 1.1 eV junction filtering the incident light.

The LIV curves measured under full spectrum AM0 illumination are illustrated in Fig. 3. The cell with 6.2% N generated a J_{sc} of 36.6 mA/cm^2 under full spectrum AM0 illumination. The open-circuit voltage (V_{oc}) of the cell was 0.13 V. A bandgap-voltage offset ($W_{oc} = E_g/q - V_{oc}$) of 0.65 V was determined for the same cell. Additionally, LIV measurements with soft concentrations were performed for the 0.78 eV junction with 6.2% N at AM1.5D spectral conditions. The cell exhibited a logarithmic dependence between concentration factor and V_{oc} of the cell, which then was used to extract an ideality factor (n) of 1.57 for the solar cell. The measured LIV characteristics for the GaInNAsSb solar cells are compiled in Table I.

TABLE I. LIV CHARACTERISTICS AT AM0 EXCITATION

[N] (%)	J_{SC} (mA/cm^2)	V_{OC} (V)	W_{OC} (V)	FF
5.3	30.5	0.31	0.54	0.62
6.0	29.0	0.20	0.60	0.50
6.2	36.6	0.13	0.65	0.40
7.9	12.7	0.07	0.66	0.24

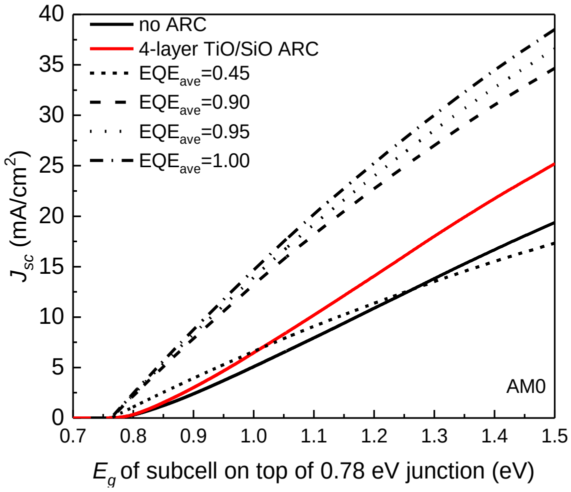

Fig. 2. Projected J_{sc} at AM0 for a 0.78 eV subcell in a multijunction architecture where incident light is filtered by a optically thick subcell. In addition, upper limits for J_{sc} for 0.78 eV subcell with different average EQEs are shown.

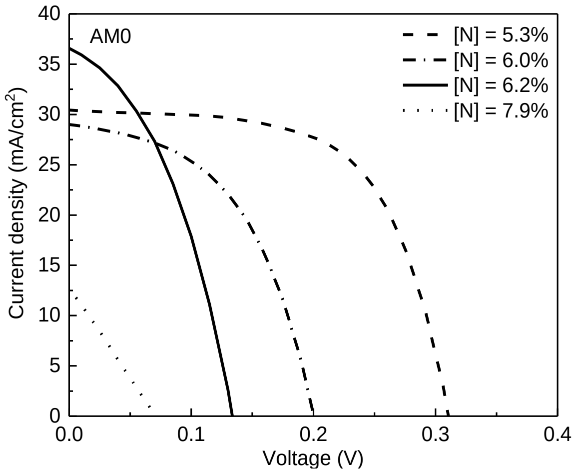

Fig. 3. Measured LIV curves for the single junction GaInNAsSb solar cells under full spectrum AM0 illumination.

Efficiency potential of a 6J design employing 0.78 eV dilute nitride subcell as the bottom junction was estimated by diode modelling using realistic parameters. An ideality factor of 1.5 was assumed for all the subcells except for the 0.78 eV junction for which 1.57 was used based on the LIV measurements. W_{oc} value of 0.65 V was used for the 0.78 eV bottom junction and W_{oc} value of 0.5 V was used for the fifth subcell. For all the other subcells, W_{oc} value of 0.4 V was chosen. For the calculations, a similar series resistance to 1 eV dilute nitride materials was assumed. In addition, the junction above the bottom subcell was assumed to be sufficiently thin to pass a fraction of the high energy photons into the bottom junction. With the 6J design employing subcells with bandgap values of 2.20 eV, 1.95 eV, 1.56 eV, 1.30 eV, 1.10 eV, 0.78 eV, and experimental parameters of the 0.78 eV bottom junction, an efficiency of ~33% was estimated at AM0 spectral conditions. The J_{sc} of the 6J was estimated to be 9.7 mA/cm^2 and the fill factor to be 0.83. With further optimization for the narrow bandgap GaInNAsSb materials, higher AM0 efficiencies exceeding 35% would be attainable.

IV. CONCLUSIONS

Single junction GaInNAsSb solar cells with high N compositions corresponding to bandgap energies below 0.8 eV are demonstrated. The cell performances were analyzed by EQE and LIV measurements. A high photocurrent of 36.6 mA/cm^2 was determined for a cell with 6.2% N and 0.78 eV bandgap energy. The measured cell characteristics were used for estimating the AM0 efficiency of a 6J cell implementing the experimental 0.78 eV GaInNAsSb junction for the bottom junction. The modelling revealed that such a 6J design could reach an efficiency of 33% for the current level of material quality demonstrated. The estimated J_{sc} and fill factor for the 6J cell were 9.7 mA/cm^2 and 0.83, respectively.

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