RADIATION RESISTANCE OF GaAs/GaSb TANDEM SOLAR CELL

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ABSTRACT: Radiation resistance of mechanically stacked tandem concentrator solar cells (SC) was studied. The photocurrent densities as high as 32.1 mA/cm^2 and 25.8 mA/cm^2 (AM0) were measured correspondingly on the IR transparent GaAs top cell and on the GaSb bottom cell in the tandem stack. Tandem SCs were irradiated with 3 MeV electrons and their performance was determined as a function of fluence up to $3{\cdot}10^{15}$cm^{-2}. It was shown that the radiation resistance of developed tandem SC increases with the top cell base doping decrease as well as with the increase of the bottom cell emitter thickness. BOL efficiency of the tandems for radiation experiment was 25.5 – 26.2% (AM0, 100 suns). EOL efficiency of 17.5% has been obtained in the tandems after 10^{15}cm^{-2} 3 MeV electron exposure.

Keywords: Tandem –1: GaAs/GaSb – 2: Radiation resistance - 3

1. INTRODUCTION

The large power requirements for space missions are determined by the priorities of solar cell parameters such as conversion efficiency and tolerance to the space radiation environment. Up to date the highest conversion efficiency of 30.5% (AM0, 100 Suns) has been achieved in the mechanical stacked GaAs/GaSb concentrator tandem cells [1]. At the same time the efficiencies as high as 26.9% (AM0, 1 Sun) [2] and 26.4% (AM0, 50 Suns) [1] have been recorded in the monolithic tandem InGaP/GaAs cell. A lot of theoretical and experimental studies of the radiation resistance of the AlGaAs, GaAs, InGaP single junction cells [3, 4, 5, 6] and monolithic tandem InGaP/GaAs cell [7, 8] have been published. Irradiation test results for GaSb and GaAs/GaSb cells are still very limited [9, 10]. In this paper the results for concentrator GaAs and GaSb cells and their mechanical tandem stacks (GaAs/GaSb) irradiated by 3 MeV electrons are presented.

2. GaAs TOP SINGLE-JUNCTION CELLS

AlGaAs/GaAs heterostructures for top cells were fabricated by low temperature liquid phase epitaxy. The structures with p^+ GaAs top contact layer, 0.03-0.05 µm wide-gap $Al_{0.8}Ga_{0.2}As$ window layer, 0.4-0.5 µm *p*-GaAs photoactive layer, 3 µm *n*-GaAs layer and back surface field $Al_{0.1}Ga_{0.9}As$ layer have been manufactured [11]. The main AlGaAs/GaAs cell peculiarities for tandem application in comparison with conventional GaAs based cells are the following: the top cell has to be transparent in the IR part of the spectrum and therefore the *n*-GaAs substrate doping density was reduced to 10^{16}-10^{17}cm^{-3}.

3. GaSb BOTTOM SINGLE-JUNCTION CELLS

3.1. The "bulk" GaSb cells

The GaSb based cells were fabricated by using "bulk" wafers (wafers prepared with bulk ingots grown by the Czochralski technique, Te doped) [10]. The GaSb wafers are exposed for the first zinc diffusion procedure by a "pseudo-closed box" technique to form a shallow *p-n* junction in photoactive area of the cells. Zn-diffuzion was performed into "bulk" GaSb wafers from pure zinc source. Anodic oxidation and selective etching were used for precise thinning the diffused GaSb layers. Under the grid fingers a deep p-n junction (0.3-1.5 µm) was formed by the second diffusion process to avoid the current leakage. Figure 1 shows the QE spectra of the cells based on "bulk" GaSb with different *p*-layer thickness. It is necessary to optimize the emitter thickness to achieve the higher photocurrent density in the developed structures and to reduce additional front layer resistance that can led to the efficiency losses at high illumination intensity. The dependence of the radiation resistance on the emitter thickness will be described below.

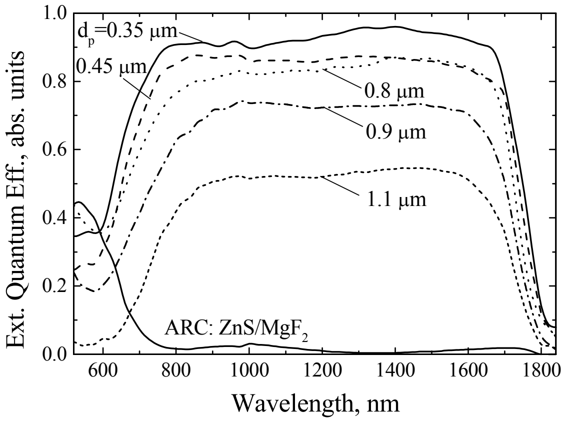

Figure 1: External quantum yield for "bulk" GaSb cells with different *p*-layer thickness. The reflectivity spectrum of MgF_2/ZnS ARC is indicated as well.

3.2. The "epitaxial" GaSb cells

Epitaxial growth of Te doped GaSb layers was carried out by liquid phase epitaxy (LPE) from Ga-rich melts. The Zn-diffusion in these epilayers was employed to form a p-n junction [10]. After that the GaSb cells were fabricated. The "spectral response - junction depth" dependences for the "epitaxial" GaSb cells are the similar to the "bulk" ones (see above).

4. ANTIREFLECTION COATINGS

Antireflection coatings (ARC) on the front and back of the AlGaAs/GaAs cell and on the front side of the GaSb cell are optimized for the reduction of reflection losses in a broader spectral region. The obtained results (Fig.2) show that it is possible to reduce optical losses in the GaAs-top and GaSb-bottom cell with a use of: a) double–layer ARCs of MgF_2/ZnS; b) prismatic covers together with a single–layer ZnS ARC. In any case the backside of GaAs had a double–layer ARC made of MgF_2/ZnS. The prismatic cover reduces the shadowing losses of the front grid but it causes some additional increased reflectance and as a result the decreased transmittance.

The optimized ARC allows to obtain the 1 Sun (AM0) photocurrent densities as high as 32.1 mA/cm^{-2} and 25.8 mA/cm^{-2} correspondingly on the IR transparent GaAs top cell and on the GaSb bottom cell in the concentrator tandem stack (the prismatic cover was used on the both cells).

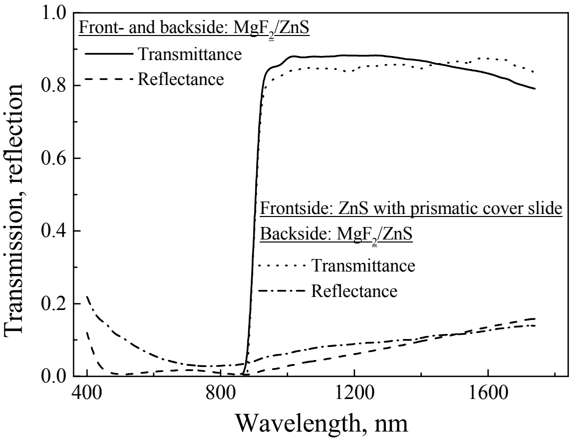

Figure 2: Measured transmittance and reflectance of AlGaAs/GaAs top cells using optimized ARC's on the front and back side of the active cell area.

However it is possible to find the grid design which ensures the low shadowing and low series resistance for concentrator cells. In this case the double–layer MgF_2/ZnS ARC for GaAs and GaSb would preferably be used.

5. RADIATION RESISTANCE OF GaAs TOP CELLS

The IR-transparent GaAs single junction cells with various junction depths were prepared to simulate the top subcell of the tandem under irradiation. The reduction of minority carrier diffusion length in the *p*- and *n*-GaAs layers were measured. The effect of electron irradiation on the spectral response was investigated for GaAs top subcells with p-n junction depth in the range of 0.1-1.0 µm. Figure 3 shows the influence of junction depth and base doping on the photocurrent density (J_{SC}) for different electron fluences.

The *p*-GaAs layer thickness of 0.4-0.5 µm in combination with low doped ($N_D=8\cdot10^{15}cm^{-3}$) *n*-GaAs base layer provides the high radiation resistance of the top subcell. On the best cell the photocurrent density as high as J_{SCO}=32.1 mA/cm^2 (1 Sun, AM0) was measured before irradiation and J_{SC}=29.7 mA/cm^2 after irradiation to a fluence of $1\cdot10^{15}$ cm^{-2}. Remaining factor is J_{SC}/J_{SCO}=0.92.

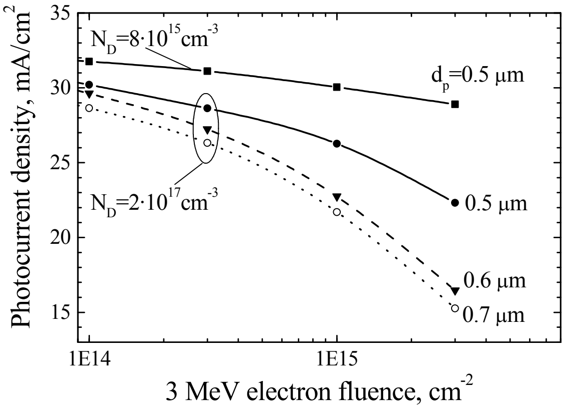

Figure 3: Photocurrent density degradation of GaAs cells after electron irradiation as a function of base doping and *p-n* junction depth.

Figure 9 shows a change of spectral responses of the GaAs top cell with low doped base. The photoresponse is negligible redused especially in the spectral range of 700-900 nm that leads to superior radiation resistance of GaAs top cell.

6. RADIATION RESISTANCE OF GaSb BOTTOM CELLS

The QE curves were measured before and after each 3 MeV electron irradiation exposure. The short circuit current density was calculated from QE data for AM0 spectrum.

The comparison of GaSb degradation without and under the GaAs filter shows that the use of high energy electrons (3 MeV) for irradiation leads to the negligible shielding of GaSb cell by GaAs top cell. Due to this effect and due to the very wide photoresponce (500 – 1850 nm) of GaSb cells we have investigated the photosensitivity degradation as well as photocurrent degradation in to aspects:

1) for whole spectral response range (500 – 1850 nm);
2) for cutted spectral response range (880 – 1850 nm) measured under GaAs top cell.

At the same time the differences in degradation for “bulk” and “epitaxial” GaSb cells are investigated.

It was observed that electron irradiation decreases the external quantum yields mainly in the long-wavelength part of GaSb solar cell spectra (Fig. 4). For thick emitters the QE value reduces in the whole photosensitivity range. The high quality “epitaxial” GaSb layers allows to increase the QE radiation stability in the long wavelength part of spectrum. The “epitaxial” GaSb cells with 0.7-0.8 µm emitter thickness demonstrate the better radiation stability of QE in IR part of photosensitivity (880 – 1850 nm) in comparison with “bulk” structure, that is very important for GaSb cell application in tandem stacks in space.

Figures 5 and 6 show the EOL j_{SC} dependence on the emitter thickness for two various spectral response ranges: whole and cutted. Under electron irradiation j_{SC} decreases rather slowly for "epitaxial" GaSb cells instead of "bulk" cells, but the degradation rate of j_{SC} depends also on the emitter thickness. The thick "epitaxial" emitter (0.8 μm) allows to conserve the high ($j_{EOL}/j_{BOL} \geq 0.89$) photocurrent value at up to $3 \cdot 10^{15}$cm^{-2} electron fluence. The emitter thickness decrease leads to the lower photocurrent degradation for "bulk" GaSb cells and vice versa for "epitaxial" ones.

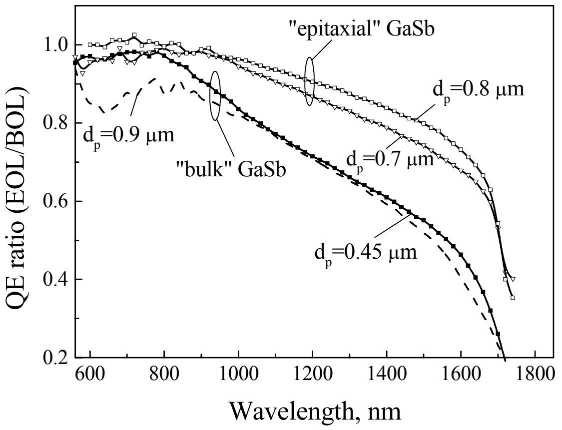

Figure 4: The EOL/BOL ratio of QE curves after $1 \cdot 10^{15}$cm^{-2} electron fluence.

Nevertheless, the high quality "epitaxial" layers in GaSb SC in combination with thick emitter demonstrates the good result in photocurrent radiation resistance for GaSb SCs.

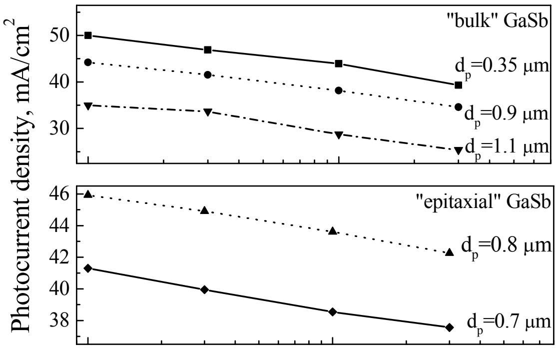

Figure 5: Photocurrent density degradation of GaSb cells after electron irradiation as a function of *p-n* junction depth. Photocurrent values are calculated for whole spectral response range.

The 3 MeV electrons with the $1 \cdot 10^{15}$ cm^{-2} fluence depresses the 5.4% initial bottom cell efficiency down to 2.9% (AM0, 100 Suns). The efficiency remaining factor (Eff_{EOL}/Eff_{BOL}) of the available GaSb cell in tandem stack is about 0.53.

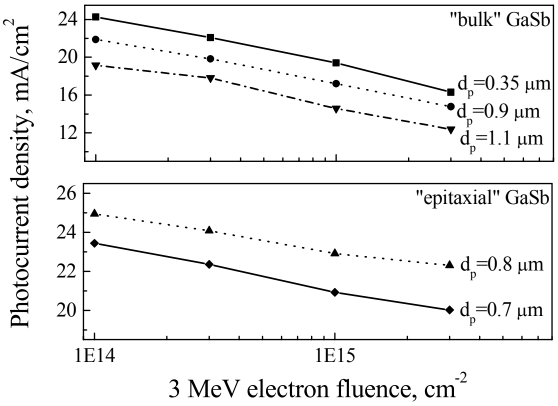

Figure 6: Photocurrent density degradation of GaSb cells after electron irradiation as a function of *p-n* junction depth. Photocurrent values are calculated for cutted spectral response range (GaSb under GaAs cell).

7. RADIATION DAMAGE FOR MECHANICALLY STACKED TANDEM GaAs/GaSb SOLAR CELLS

The maximum efficiencies achieved in four terminal mechanically stacked tandem are 26.5% at 100 suns (AM0) and 25.1% at 20 suns (AM0) (Fig. 7). On both cells the prismatic cover is applied.

The efficiency of 23.7% (AM0, 10 suns) has been measured on the two terminal triplets manufactured for linear receiver (the top and bottom cells are out of prismatic cover).

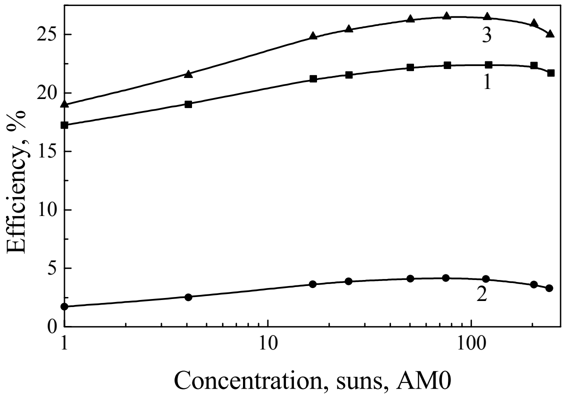

Figure 7: Mechanically stacked tandem cell efficiency (AM0, 25^{0}C) versus concentration ratio: AlGaAs/GaAs top IR-transparent cell (1), GaSb bottom cell (2), the sum of these efficiencies (3).

GaAs/GaSb tandem cells stacks have been irradiated by 3 MeV electrons. BOL efficiency of the cells for this experiment was 25.5 – 26.2% (AM0, 100 suns). The 17.5% EOL efficiency and 0.68 remaining factor of efficiency have been recorded in the GaAs/GaSb tandem after $1 \cdot 10^{15}$cm^{-2} 3 MeV electron exposure (Fig. 8). Figure 9 shows the absolute spectral responses of the mechanical stacked tandem cell before and after 3 MeV electron irradiation up to $3 \cdot 10^{15}$ cm^{-2} fluence.

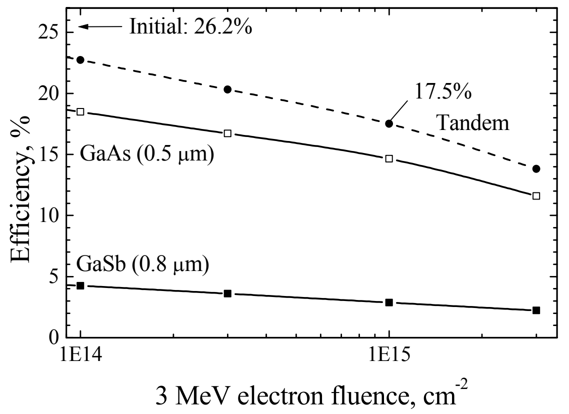

Figure 8: The efficiency degradation of GaAs/GaSb concentrator SC as a function of 3 MeV electron fluence (AM0, 100 Suns).

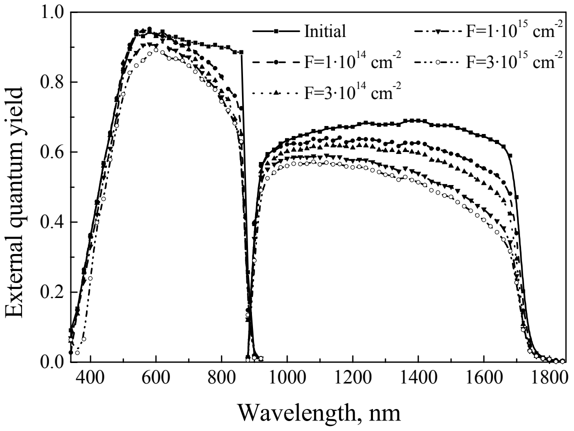

Figure 9: External quantum yield of the GaAs/GaSb-tandem cell with 0.5 μm junction depth in the top GaAs subcell and 0.8 μm junction depth in the bottom GaSb subcell as a function of 3 MeV electron fluence. Base doping level of $8\cdot10^{15}$ cm^{-3} is in the GaAs subcell.

SUMMARY

The radiation resistance was investigated for GaAs/GaSb mechanically stacked tandem concentrator solar cells with beginning of life efficiency in the range of 25.5 – 26.5% (AM0, 100 suns). The best device was shown to retain approximately 67% of its initial efficiency after $1\cdot10^{15}cm^{-2}$ 3 MeV electron exposure. This degradation can be reduced in the GaSb cells with high quality epitaxial layers. The primary degradation was a result of a large loss of photocurrent from the GaSb bottom cell owing to use of the high energy electrons (3 MeV) for irradiation. At lower electron energies (for example at widely used 1 MeV electrons), the GaAs top cell with cover glass made available the enhance effective shielding of GaSb cell.

With low base doping in the top GaAs cell and appropriate emitter thickness in the "epitaxial" GaSb bottom cell, an EOL AM0 efficiency of 20% can be achieved at $1\cdot10^{15}cm^{-2}$ 1 MeV electron fluence.

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