Radiation tolerance of $GaAs_{1-x}Sb_x$ solar cells: A candidate III-V system for space applications

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Abstract— **The high radiation tolerance of $GaAs_{0.86}Sb_{0.14}$ based solar cells with a band gap suitable for PV is demonstrated at the low intensity low temperature (LILT) conditions. This system shows remarkable radiation hardness at AM0, and more prominently, at the conditions of several outer planetary targets. This is attributed to an irradiation induced change in the absorber band gap due to local heating and strain relaxation, and the generation of less prohibitive shallow Sb-based defects in the $GaAs_{1-x}Sb_x$ absorber.**

Keywords— ***$GaAs_{1-x}Sb_x$, LILT, radiation tolerance***

I. INTRODUCTION

Evolution of satellites and spacecrafts has created an accelerating business with its base in space. This new space economy is mostly fueled by solar power. High quality solar panels and batteries are used to power the electronics on the crafts and satellites to keep them operational. A satellite commonly experiences high radiation levels and abrupt temperature fluctuations, so the environment in space is harsher on electronic devices when compared to terrestrial applications. High efficiency and radiation tolerance are essential factors required for solar panels working in space. Currently, III-V multi-junction solar cells provide highest efficiency and are commonly used in space [1, 2].

Since junctions of a tandem solar cell are normally stacked in series and the generated photocurrent is the minimum of the currents produced by any of the junctions, damage in one junction limits the current of all the other layers as well. As a result, radiation tolerance of such systems, particularly in deep space brings added complexity to their design since there is large variability in the sub cell radiation tolerance [2-4]. Although, numerous research efforts have targeted improving radiation resistance of the tandem structures [5-8], a relatively thick cover glass is still required to shield and protect the cells against irradiation at space; this in turn increases the weight and reduces the specific power of the systems.

Recently, ultrathin GaAs has been shown to offer potential as a more radiation hard system for space [9], if appropriate optical management can be designed to improve the absorption. Here, GaAsSb is proposed as a candidate material for space power applications, particularly in the regions of harsh radiation conditions of outer space and under low-intensity-low-light (LILT) conditions. Remarkably high radiation tolerance of optically *thick* and optimally designed $GaAs_{0.86}Sb_{0.14}$ without encapsulation is presented. Experimental results suggest this system should be further considered for hostile space missions including those to Jupiter or for satellite applications in Highly Eccentric Orbits (HEO). Series of satellites in this orbit are being considered to provide better internet coverage and navigation accuracy, which require more robust systems.

Experimental

A $GaAs_{1-x}Sb_x$ based p-i-n solar cell was grown using solid source molecular beam epitaxy on n^+-GaAs (100) substrates. The device consists of a 100 nm n-type GaAs buffer layer doped with silicon (1×10^{18} cm^{-3}) grown at 580°C. This was followed by a 400 nm base consisting of graded n-type $GaAs_{1-x}Sb_x$ to provide strain compensation – in order to balance the mismatch in the lattice constant between GaAs and $GaAs_{1-x}Sb_x$ while achieving high quality material at the required composition in the active region. The quality of the growth process is confirmed by transmission electron microscopy (TEM) and shown in Figure 1(b).

The n-type (2×10^{17} cm^{-3}) strain-balanced $GaAs_{1-x}Sb_x$ was grown at 510°C followed by a 30 nm n-AlGaAsSb back-surface-field (BSF) layer doped with silicon at 2×10^{18} cm^{-3}. The buffer layer was followed by a 1000 nm base of n-type $GaAs_{0.86}Sb_{0.14}$ and 500 nm of nominally undoped $GaAs_{0.86}Sb_{0.14}$. The i-region acts as the main absorber of the device, while allowing assessment of the background impurity concentration in the material. A 150 nm Be-doped p-type $GaAs_{0.86}Sb_{0.14}$ emitter (1×10^{18} cm^{-3}), 30 nm p-type AlGaAsSb window layer (1×10^{18} cm^{-3}), and a final 20 nm p^+-$GaAs_{0.86}Sb_{0.14}$ cap layer completed the design of the p-i-n structure, shown in Figure 1. Devices were fabricated using conventional wet-etching techniques and optical lithography into mesa diodes of average area ~ 0.25 cm^2. The contacts were deposited using thermal evaporation with a Zn-Au grid pattern and a Ni-Ge-Au layer for the upper p-type and lower n-type contacts, respectively. The samples were annealed at 400˚C for 60 s to facilitate good ohmic contacts.

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II. RESULTS AND DISCUSSION

A schematic of the GaAsSb based solar cell structure is shown in Figure 1(a), while a high-resolution cross sectional (X)-TEM image of the high-quality active layers with no observable dislocation defects is shown in Figure 1(b). The bulk p, i, and n-GaAsSb absorber is encapsulated in AlGaAsSb window and BSF layers, evident as the brighter regions. Growth defect formation and strain relaxation appear to be confined to the conductive buffer substrate region at the base of the cell, away from the active region device.

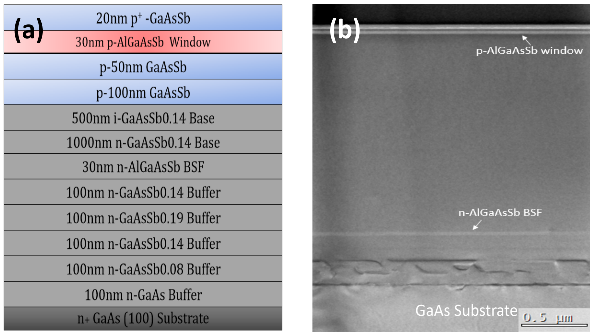

Figure 1: (a) Schematic illustration of the GaAsSb based solar cell, (b) TEM cross section of the layers of the cell.

Figure 2 shows the effect upon the PV characteristic before (black) and after (red) the $GaAs_{0.86}Sb_{0.14}$ solar cell is irradiated with 1-MeV electrons at a fluence of 1×10^{15} electrons/cm^2. Comparing the 1-sun AM0 current density-voltage (*J-V*) response in Figure 2(a), the irradiated device (red) demonstrates a significant reduction in J_{SC}, while the V_{OC} is relatively unaffected. The reduced J_{SC} is reflected in the reduced EQE shown in Figure 2(b) throughout the main absorber region. Prior to irradiation, the EQE (black) begins to absorb at ~ 1100 nm, which is the band gap of the bulk $GaAs_{0.86}Sb_{0.4}$ absorber, increasing slowly and peaking at ~ 700 nm; the band gap energy of the AlGaAsSb window and BSF layers. The slope in the EQE towards longer wavelengths is indicative of a reduced minority carrier diffusion length in the nominally intrinsic ~ 0.5 μm $GaAs_{0.86}Sb_{0.14}$. This is related to a combination of unintentional allow fluctuations and background impurities, both of which are observed in temperature dependent photoluminescence experiments (not show here for brevity).

The consequences of these material issues are that the thick intrinsic region is not fully depleted, resulting in significant recombination losses deep in the $GaAs_{0.86}Sb_{0.4}$. This is due to the insufficient diffusion of (predominately) minority holes outside of the space charge region. Interestingly, this results in bright PL; indicating these losses are *not* primarily dominated by parasitic mid gap states and associated non-radiative losses. This is also supported by the retention of the V_{oc} in Figure 2(a) and similar dark current density values before and after irradiation (not shown here). Similar effects are observed in the dilute nitrides, where indium and nitrogen fluctuations result in limited the carrier transport and enhanced radiative recombination [10].

After irradiation, in addition to the monatomic decrease in EQE, a shift in the absorption edge to shorter wavelengths is also evident for both GaAsSb and AlGaAsSb transitions as observed in Figure 2(b). The combination of this radiation induced blueshift, coupled with the retention in the overall shape of the EQE further suggest the effects of the irradiation is not simply the creation of non-radiative centers but rather changes in the absorber due to the strain and/or composition of the Sb-based materials. Indeed, no significant or catastrophic damage was observed in X-TEM images taken after irradiation (not shown for brevity).

Stopping and range of ions in matter, or SRIM, calculations will be performed to assess the magnitude of energy loss 1MeV electrons have within the absorber region relative to other regions of the device. The main effect of the irradiation can be attributed predominantly to inelastic energy loss and the generation of shallow Sb-based defects, which affects the ternary composition and consequently the absorber band gap, along with the strain balance of the system – as observed in Figure 2(b). This displacement and migration of Sb would also affect the local alloy fluctuations in the material, evidence of which can be seen in PL measurements, with support from SRIM simulations and displacement (vacancy) calculations, which will be presented later.

While the carrier extraction and therefore performance of the solar cell the $GaAs_{0.86}Sb_{0.4}$ is reduced upon irradiation, the enhanced radiative minority carrier recombination can be attributed to shallow Sb-based alloy fluctuations rather than non-radiative recombination. This interestingly results in the V_{oc} and dark current before and after electron exposure being relatively unaffected by the radiation.

Figure 3 shows the performance of the pre- (black) and post- (red) irradiated solar cell in LILT conditions governing the outer planetary objects of Saturn and Jupiter and Mars.

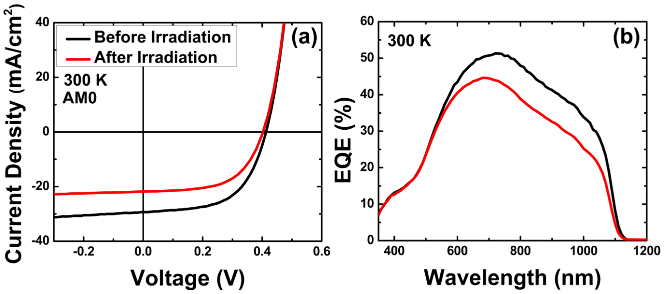

Figure 2: (a) Current Density-Voltage (JV) results at room temperature for before (black) and after (red) irradiation. (b) External Quantum Efficiency (EQE) results at room temperature for before (black) and after (red) irradiation.

While in all cases, there are reductions in V_{oc} and J_{sc} relative to room temperature AM0; these simply reflect the systematic lowering of illumination and temperature for the planetary conditions under investigation. Interestingly, the effects of irradiation are, in the environments of Saturn and Jupiter (Figures 3(a) and (b)), *negligible*. In the case of Mars, similar to AM0 at room temperature, the V_{OC} remains unchanged while J_{SC} is reduced, despite the increase in illumination intensity and thermal energy of carriers.

Whilst this behavior is somewhat counterintuitive; the increased intensity levels and temperature appear to have a more detrimental impact on device performance after irradiation. This effect is evident considering the further loss in performance observed at AM0 (Figure 2). Several potential reasons for the improved performance of the GaAsSb solar cell at LILT conditions with respect to ambient will be discussed. These include the role of a parasitic barrier and the subsequent effects of this unintentional barrier to larger photogenerated minority carrier populations at higher temperatures [11]. Additionally, the effects of the background impurity concentration on defect formation and the doping profile of the device upon irradiation, would explain the results observed [9, 12].

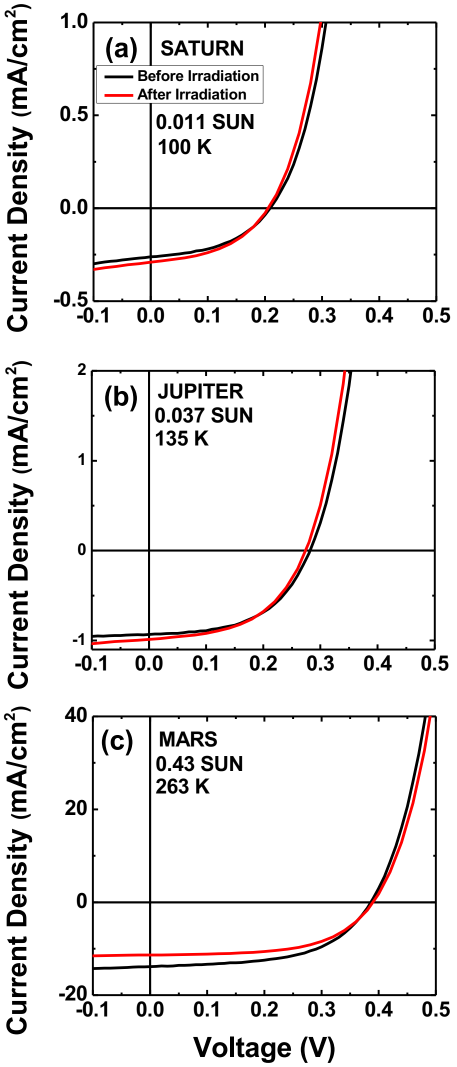

Figure 3: J-V curves at AM0 intensity before (black) and after (red) irradiation for the LILT conditions of (a) Saturn, (b) Jupiter, and (c) Mars.

III. CONCLUSIONS AND SUMMARY

The radiation tolerance of a GaAs$_{1-x}$Sb$_x$ based solar cell is presented under LILT conditions. Remarkably high radiation resistance is observed in the PV parameters, particularly in LILT conditions compared to AM0. While the reduced cell performance is evident at AM0, this appears related to increased radiative recombination and compositional fluctuations, rather than parasitic non-radiative recombination loss. Furthermore, an unusual increase in the J_{SC} is observed upon irradiation at low temperatures with a negligible effect upon V_{oc} at all conditions assessed here. The potential origins of the remarkable radiation tolerance of this material will be discussed.

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REFERENCES

[1] T. Markvart, A. McEvoy, L. Castaner, Practical handbook of photovoltaics: fundamentals and applications, Elsevier, 2003.

[2] S. Kalogirou, McEvoy's handbook of photovoltaics: fundamentals and applications, Academic Press, 2017.

[3] M. Imaizumi, T. Nakamura, T. Takamoto, T. Ohshima, M. Tajima, Radiation degradation characteristics of component subcells in inverted metamorphic triple‐junction solar cells irradiated with electrons and protons, Progress in Photovoltaics: Research and Applications, 25 (2017) 161-174.

[4] J. Parravicini, F. Arcadi, A. Le Donne, R. Campesato, M. Casale, E. Greco, S. Binetti, Effect of the irradiation on optical and electrical properties of triple-junction flexible thin solar cells for space applications, Frontiers in Physics, 7 (2019) 169.

[5] M. Yamaguchi, Radiation-resistant solar cells for space use, Sol. Energy Mater. Sol. Cells, 68 (2001) 31-53.

[6] R.H. van Leest, D. Fuhrmann, A. Frey, M. Meusel, G. Siefer, S.K. Reichmuth, Recent progress of multi-junction solar cell development for CPV applications at AZUR SPACE, in: AIP Conference Proceedings, AIP Publishing LLC, 2019, pp. 020007.

[7] A.W. Bett, F. Dimroth, W. Guter, R. Hoheisel, E. Oliva, S.P. Philipps, J. Schöne, G. Siefer, M. Steiner, A. Wekkeli, Highest efficiency multi-junction solar cell for terrestrial and space applications, space, 25 30.36.

[8] G.A. Landis, J. Fincannon, Study of power options for Jupiter and outer planet missions, in: 2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC), IEEE, 2015, pp. 1-5.

[9] L. Hirst, M. Yakes, J. Warner, M. Bennett, K. Schmieder, R. Walters, P. Jenkins, Intrinsic radiation tolerance of ultra-thin GaAs solar cells, Applied Physics Letters, 109 (2016) 033908.

[10] M. Fukuda, V. R. Whiteside, J. C. Keay, A. Meleco, I. R. Sellers, K. Hossain, T. D. Golding, M. Leroux, M. Al Khalfioui, Improved performance in GaInNAs solar cells by hydrogen passivation, Applied Physics Letters 106 (2015), pp. 141904

[11] C. R. Brown, G. E. Eperon, V. R. Whiteside, I. R. Sellers, Potential of High-Stability Perovskite Solar Cells for LILT outerp lanteray mission, ACS Applied Energy Materials, 2 (2018), pp. 814

[12] R.J. Walters, S. Messenger, J.H. Warner, C.D. Cress, M. Gonzalez, S. Maximenko, Modeling of radiation induced defects in space solar cells, in: Physics and Simulation of Optoelectronic Devices XIX, International Society for Optics and Photonics, 2011, pp. 79330P