Electron irradiation study of metamorphic 1.7 eV GaAsP solar cells

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***Abstract*— We investigated the effects of 1 MeV electron irradiation on uncoated metamorphic ~1.7 eV GaAsP solar cells on GaP and on GaP/Si. Effects of junction polarity, base thickness, and threading dislocation density on radiation hardness were investigated using the AM0 solar simulator at NASA Glenn Research Center. Degradation of solar cell efficiency after irradiation was dominated by reduced minority carrier diffusion length in the base, leading to loss of long-wavelength carrier collection. Designs with higher base diffusion length or thinner base were favored, and accordingly, devices with n^+/p junction polarity were more radiation-hard than those with p^+/n junction polarity.**

***Keywords*— III-V/Si solar cells, GaAsP, electron irradiation**

I. INTRODUCTION

The ongoing interest in epitaxial 1.7 eV/1.1 eV III-V/Si solar cells stems from the calculated potential for a 34–40% (37–44%) tandem efficiency under the AM0 (AM1.5G) spectrum [1]–[2], all while utilizing a low-cost, large-area, and high-volume Si substrate. Lattice-mismatched (metamorphic) growth is required to integrate 1.7 eV junctions on Si, leading to high threading dislocation density (TDD) in the III-V layers and limited efficiency. However, recent advances have enabled improved material quality and efficiency [3]–[6]. As the performance of III-V/Si solar cells increases, these designs are expected to be of greater interest for space applications due to the possibility of realizing high efficiency on a low-cost Si platform. ~1.7 eV $GaAs_{0.77}P_{0.23}$ (hereafter GaAsP) has received considerable attention as the top junction of a tandem with Si, but only limited studies of GaAsP solar cell irradiation effects currently exist in the literature [7]–[8].

In this work, we performed 1 MeV electron irradiation studies of GaAsP solar cells, here testing the effects of junction polarity, base thickness, and TDD on radiation hardness. Loss of long-wavelength carrier collection reduced the efficiency after irradiation and favored designs with higher minority carrier diffusion length in the base or a thinner base. The change from p^+/n to n^+/p junction polarity resulted in the largest increase of radiation hardness with the n^+/p design having ~0.94 remaining factor for efficiency after a 1×10^{15} e/cm^2 fluence.

II. EXPERIMENTAL

All samples were grown in a Veeco Mod GEN-II solid-source molecular beam epitaxy (MBE) system and fabricated into devices without anti-reflection coating (ARC), as described previously [9]. Growth was performed on either bulk GaP (001) substrates or GaP on Si (001) templates (NAsP$_{III/V}$ GmbH, similar to [10]) consisting of a ~40 nm GaP nucleation layer on Si. Fig. 1 shows the schematic layer structure for a fabricated solar cell including a nominally lattice-matched InGaP window layer, a GaAsP emitter, base, and doping back surface field (BSF) on top of a $GaAs_yP_{1-y}$ step-graded buffer and GaP buffer layer. Dopant concentration was graded from 2×10^{18} cm^{-3} at the end of the graded buffer to 1×10^{17} cm^{-3} at the start of the base to

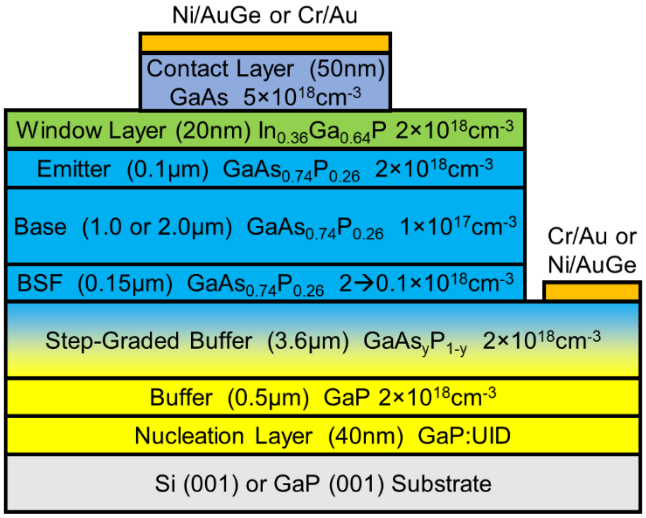

Fig. 1. Schematic layer structure for fabricated GaAsP solar cells; no ARC was applied. Dopant concentrations are shown, and the dopant atom (Si for *n*-type, or Be for *p*-type) used for each layer depends on junction polarity. Ni/AuGe (Cr/Au) metal contacted *n*-type (*p*-type) material.

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TABLE I.
SUMMARY OF SOLAR CELL DESIGN VARIANTS TESTED FOR COMPARISONS OF EFFECTS OF TDD, BASE THICKNESS, AND JUNCTION POLARITY. THE TDD WAS ESTIMATD BY ELECTRON BEAM-INDUCED CURRENT (EBIC) IMAGES [9].

Variant	Polarity	t_{base} (µm)	Substrate	TDD (cm^{-2})	E_G (eV)
1 – Control	p^+/n	2	GaP	7.6×10^6	1.732
2 – Higher TDD	p^+/n	2	GaP/Si	1.3×10^7	1.740
3 – Thinner Base	p^+/n	1	GaP	7.4×10^6	1.741
4 – $n+/p$ Polarity	n^+/p	2	GaP	6.4×10^6	1.748

form the GaAsP doping BSF. Several solar cell design variants, as listed in Table 1, were investigated in this study to compare the effects of TDD, base thickness (t_{base}), and junction polarity on radiation hardness. As these solar cells were stored in air and room light for over six years, each sample was retested to ensure only minor performance loss and to obtain a set of measurements before irradiation.

Uncoated solar cells were irradiated at the NEO Beam facility at room temperature with 1 MeV electrons to a fluence of 1×10^{15} e/cm^2. Device performance characterization was determined before (beginning-of-life, BOL) and after electron irradiation (end-of-life, EOL) by external/internal quantum efficiency (EQE/IQE), dark/lighted current-voltage (DIV/LIV), and Suns-V_{OC} measurements. EQE and reflectance were performed in a PV Measurements QEX7 system to calculate IQE and bandgap (E_G). AM0 LIV measurements were performed at NASA Glenn Research Center on their custom triple source AM0 solar simulator, including a Spectrolab X-25 and filtered and unfiltered tungsten halogen lamps [11]. AM0-calibrated SolAero ZTJ isotype cells were used to calibrate the three sources for approximate 1-sun AM0 illumination.

III. RESULTS AND DISCUSSION

Fig. 2 shows a comparison of the figures of merit (V_{OC}, J_{SC}, and efficiency) at BOL for the best device of each variant under AM0 illumination; Table 2 includes values for bandgap-voltage offset ($W_{OC} = E_G/q - V_{OC}$) and fill factor (FF) as well. Samples on GaP substrates had W_{OC} of 0.57–0.58 V, while the sample on the GaP/Si template had a higher W_{OC} of 0.63 V due to its higher TDD. In comparison to variant 1, J_{SC} decreased due to reduced long-wavelength collection for either a higher TDD (variant 2) due to lower minority carrier diffusion length, or a thinner base (variant 3) due to incomplete absorption. Though J_{SC} was improved for reversed polarity to n^+/p (variant 4) in comparison to the p^+/n control (variant 1), variant 4 had lower BOL efficiency due to poor fill factor, which will be discussed in detail below.

Remaining factors after electron irradiation with 1×10^{15} e/cm^2 fluence are given in Fig. 3 for each variant tested, showing that performance degradation from irradiation resulted primarily from reduced J_{SC}. Table 2 includes values of BOL, EOL, and remaining factors for each figure of merit and each variant. Consistent with earlier studies having high base doping in the low 10^{17} cm^{-3} range [12], the relative loss in V_{OC} was considerably less than the relative loss in J_{SC}. While for low base doping, the carrier concentration is significantly compensated

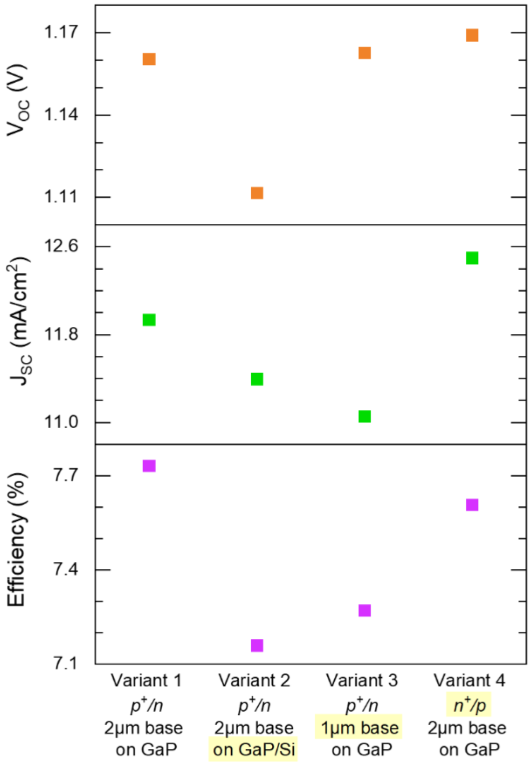

Fig. 2. Uncoated BOL figures of merit for GaAsP solar cell variants as determined from 1-sun AM0 LIV of each best device. Highlighted text indicates the difference from variant 1.

TABLE II.
AM0 FIGURES OF MERIT BEFORE AND AFTER 1 MEV ELECTRON IRRADIATION TO 1×10^{15} E/CM^2 AND THE RESULTING REMAINING FACTORS.

Variant	V_{OC} (V)	W_{OC} (V)	J_{SC} (mA/cm^2)	FF (%)	Efficiency (%)
	BOL Measurements				
1 – Control	1.160	0.572	11.93	76.3	7.73
2 – Higher TDD	1.112	0.629	11.39	77.2	7.16
3 – Thinner Base	1.163	0.578	11.05	77.3	7.27
4 – $n+/p$ Polarity	1.169	0.579	12.50	71.1	7.61
	EOL Measurements				
1 – Control	1.120	0.612	10.53	75.0	6.47
2 – Higher TDD	1.090	0.651	9.97	72.6	5.77
3 – Thinner Base	1.117	0.628	10.03	75.1	6.16
4 – $n+/p$ Polarity	1.128	0.620	11.98	72.1	7.13
	Remaining Factors (EOL/BOL)				
1 – Control	0.965	–	0.882	0.983	0.837
2 – Higher TDD	0.980	–	0.875	0.940	0.806
3 – Thinner Base	0.961	–	0.908	0.971	0.847
4 – $n+/p$ Polarity	0.965	–	0.959	1.013	0.937

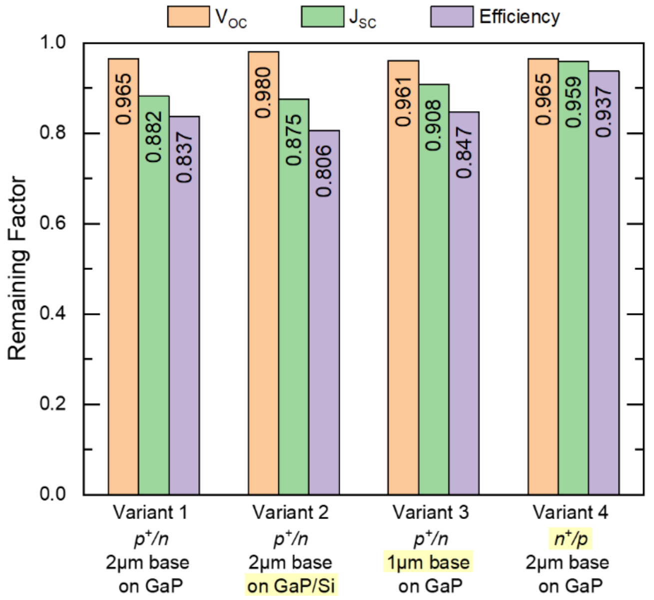

Fig. 3. Remaining factors of figures of merit for GaAsP solar cell variants after irradiation with 1 MeV electrons to a fluence of 1×10^{15} e/cm^2, as determined from 1-sun AM0 LIV of each best device. Highlighted text indicates the difference from variant 1.

by point defects introduced as radiation damage and leads to larger depletion width and therefore more V_{OC} loss than J_{SC} loss, high base doping is minimally affected by compensation [12]. Instead for high base doping, the major effect of radiation damage is shortened minority carrier diffusion length from more defective material. With shorter diffusion length, carrier collection far from the junction is poor, and as expected, variant 3 with a thinner 1 μm base had higher remaining factor for J_{SC}. Another observation is that variant 2, with a higher TDD, showed less V_{OC} degradation as the added point defects from irradiation influenced the overall defect density less, lowering V_{OC} by ~20 mV on GaP/Si as opposed to ~40 mV for the lower TDD on GaP.

The n^+/p variant 4 had superior radiation hardness to the p^+/n variant 1 due to the longer minority carrier diffusion length of electrons over holes in the respective base regions. Similar to GaAs, electron diffusivities in GaAsP are estimated to be ~11–13× higher than hole diffusivities [13]. IQE comparison between the p^+/n and n^+/p designs in Fig. 4(a) showed that the p^+/n variant 1 had higher short-wavelength IQE, while the n^+/p variant 4 had higher long-wavelength IQE. Ultimately, the n^+/p design was more radiation hard than the p^+/n design due to the higher minority electron diffusivity in the thick *p*-GaAsP base.

With smaller J_{SC} degradation, the n^+/p variant 4 achieved the highest EOL efficiency among the samples tested with 7.13% efficiency under AM0 illumination as compared to 6.47% for the p^+/n variant 1. However as mentioned earlier, variant 4 suffered from low FF (71–72% versus 75–76%), as shown in the comparison of BOL and EOL LIV (Fig. 4(b)). Analysis of DIV and Suns-V_{OC} (inset Fig. 4(b)) showed the major cause of poor FF for variant 4 to be high series resistance, due to high contact resistance. For the n^+/p variant 4, DIV bends over due to series resistance at about an order of magnitude lower current density, indicating nearly 10× higher series resistance and leading to a reduced max power point voltage for LIV.

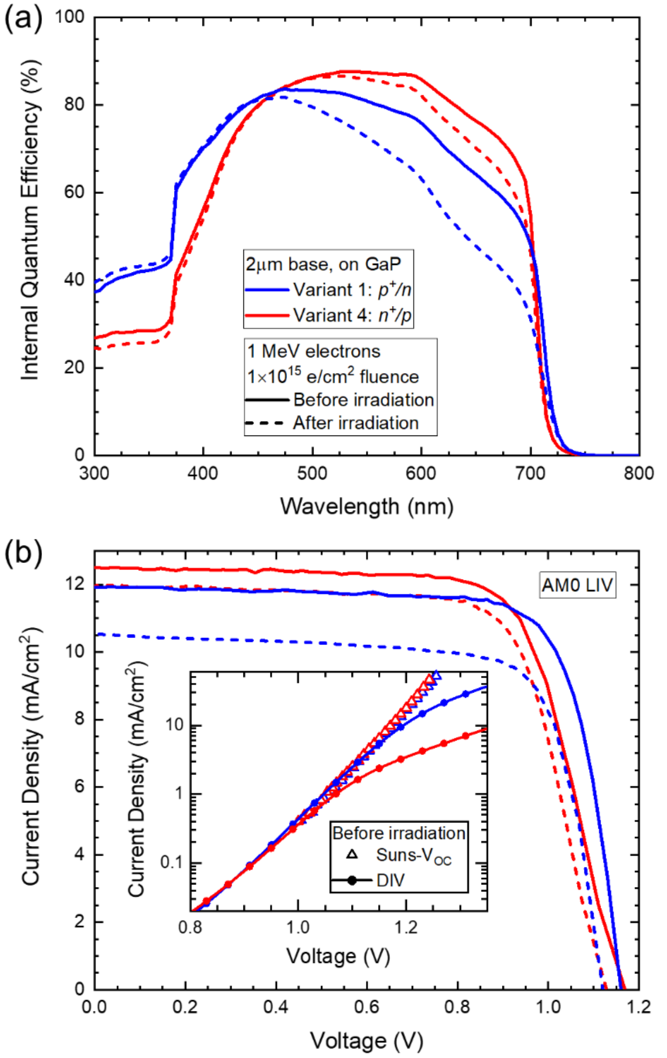

Fig. 4. Best device performance for variant 1 and variant 4 to compare reversed junction polarity. Comparison of BOL and EOL (a) IQE and (b) 1-sun AM0 LIV. DIV and Suns-V_{OC} for these two samples at BOL are inset in (b).

IV. CONCLUSIONS

We investigated the performance of metamorphic ~1.7 eV GaAsP solar cells before and after 1 MeV electron irradiation including comparisons for TDD, base thickness, and junction polarity. Performance degradation from irradiation was dominated by decreased J_{SC} arising from reduced minority carrier diffusion length in the base. Due to this sensitivity to base diffusion length, the n^+/p junction polarity had superior radiation hardness compared to the p^+/n design. Future work will investigate the radiation hardness of our n^+/p ~1.7 eV GaAsP solar cells on GaP/Si with improved material quality and device design, which enabled W_{OC} down to 0.525 V and AM1.5G efficiencies up to 15.3–16.5% [5], [14]. Various designs will be studied to understand how design changes affect radiation hardness, such as use of an InGaP BSF, thinner emitter, InAlP window layer, highly-doped contact layer, and ARC [3], [5], [9], [14], [15].

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