

# Effect of Threading Dislocations on GaInP Front- and Rear-Junction Solar Cells Grown on Si

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**Abstract**—We compare the performance of front-junction (FJ) and rear-heterojunction (RHJ) 1.9 eV GaInP solar cells grown on Si by molecular beam epitaxy. First, time-resolved photoluminescence showed a minority carrier lifetime of 11.7 ns for *n*-GaInP on Si, indicating a high tolerance to threading dislocations due to the low mobility of minority holes. GaInP solar cells were grown on both GaAs and Si substrates in FJ (*p*-type absorber) and RHJ (*n*-type absorber) configurations. The internal quantum efficiency (IQE) of FJ cells was identical on GaAs and Si substrates and showed high IQE-derived short-circuit current density  $J_{SC,IQE} > 14 \text{ mA/cm}^2$ , suitable for high-efficiency multijunction cells, while RHJ cells showed diminished  $J_{SC,IQE} < 11 \text{ mA/cm}^2$  due to limited diffusion length and high sensitivity to front-surface recombination. The RHJ cells on Si maintained a high open-circuit voltage ( $V_{OC}$ ) of 1.292 V with threading dislocation density (TDD) of  $1.0 \times 10^7 \text{ cm}^{-2}$ , a similar  $V_{OC}$  value to FJ cells grown lattice-matched on GaAs. In addition, for a high TDD of  $2.7 \times 10^8 \text{ cm}^{-2}$ , RHJ cells had a  $V_{OC}$  of 1.223 V, greater than FJs with  $10\times$  lower TDD of  $2.7 \times 10^7 \text{ cm}^{-2}$ , which further shows the high dislocation tolerance of *n*-GaInP. The high  $V_{OC}$ , combined with the proposed work to boost IQE, could enable GaInP RHJs on Si for multijunction cell applications.

**Index Terms**—GaInP, III-V on Si, metamorphic, molecular beam epitaxy (MBE).

## I. INTRODUCTION

SINGLE-JUNCTION (1J) Si solar cells, by far the most dominant photovoltaic technology, are approaching their fundamental efficiency limit of 29.4% [1] at both the laboratory and commercial scale [2]. Multijunction solar cells (MJSCs) using a Si bottom cell have theoretical efficiencies of 37%–44% [3], [4] for 2- and 3-junctions, respectively, and are a promising

approach to reduce cost per watt. III–V on Si MJSCs use a variety of integration approaches, such as wafer bonding, mechanical stacking, and direct growth. Both wafer bonding and mechanical stacking have achieved record III–V/Si MJSC efficiencies of 35.9% [5], [6], well beyond the Si single-junction efficiency limit. In contrast, while the efficiency of epitaxial III–V/Si cells has increased significantly in recent years [7], [8], [9], the record efficiency of 25.9% [9] is well below bonded and mechanically stacked cells due to nonradiative recombination at threading dislocations. Despite the lower efficiency, a key advantage of direct growth is its simpler fabrication process, which could enable greater scalability.

Yamaguchi's model of the effect of dislocations on minority carrier lifetime  $\tau$  is given as [10]

$$\frac{1}{\tau} = \frac{1}{\tau_0} + \frac{1}{\tau_{TDD}} \quad (1)$$

where  $\tau_0$  is the nominal lifetime for dislocation-free material, while  $\tau_{TDD}$  is the nonradiative lifetime due to dislocations. In this equation,  $\tau_{TDD}$  is further defined as

$$\tau_{TDD} = \frac{4}{\pi^3 D \text{TDD}} \quad (2)$$

where  $D$  is the minority carrier diffusivity and TDD is the threading dislocation density. Since electrons have  $\sim 10\text{--}20\times$  higher diffusivity than holes in most direct-gap III–V absorber materials, cells with a primarily *p*-type absorber (relying on the collection of minority electrons) are more sensitive to TDD than those with a primarily *n*-type absorber (relying on collection of minority holes). In *p*-GaAs, lifetime degrades more rapidly than in *n*-GaAs as a function of TDD [11], and, accordingly, open-circuit voltage ( $V_{OC}$ ) of  $n^+/p$  GaAs solar cells degrade more strongly with increasing TDD than  $p^+/n$  cells at a given TDD [12]. Nevertheless, the high diffusivity of minority electrons in *p*-GaAs can enable reasonable diffusion length and carrier collection of minority electrons in the presence of dislocations, as exemplified by the high  $J_{SC}$  of 26.5 mA/cm<sup>2</sup> for  $n^+/p$  front-junction (FJ) GaAs cells on Si with TDD of  $7 \times 10^6 \text{ cm}^{-2}$  [13].

GaInP cells show greater experimental dislocation tolerance than GaAs in external quantum efficiency (EQE) and open-circuit voltage ( $V_{OC}$ ) [7], [8], [14]. The EQE-derived short-circuit current density of epitaxial GaInP cells on Si ranges from 12.2 to 13.0 mA/cm<sup>2</sup>, with more recently reported cells thinned to 390–400 nm to improve current matching to the underlying GaAs subcell [8], [9]. In addition, subcell GaInP  $V_{OC}$  extracted from electroluminescence (EL) showed  $V_{OC}$  loss on Si exceeding 100 mV for TDD in the range of  $2.2 \times 10^7\text{--}1.4 \times 10^8 \text{ cm}^{-2}$

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100 nm n-AlInP barrier $n = 1 \times 10^{18} \text{ cm}^{-3}$	100 nm p-AlGaInP barrier $p = 1 \times 10^{18} \text{ cm}^{-3}$
500 nm n-GaInP absorber $n = 1 \times 10^{17} \text{ cm}^{-3}$	500 nm p-GaInP absorber $p = 1 \times 10^{17} \text{ cm}^{-3}$
100 nm n-AlInP barrier $n = 1 \times 10^{18} \text{ cm}^{-3}$	100 nm p-AlGaInP barrier $p = 1 \times 10^{18} \text{ cm}^{-3}$
100 nm n <sup>+</sup> -GaAs buffer	100 nm p <sup>+</sup> -GaAs buffer
500 nm UID-GaAs buffer	500 nm UID-GaAs buffer
<b>SI-GaAs or GaAs/Si (001)</b>	<b>SI-GaAs or GaAs/Si (001)</b>

(a) (b)

Fig. 1. Layer structures for (a) *n*-GaInP and (b) *p*-GaInP DHs grown on semi-insulating (SI) GaAs and on GaAs/Si (001).

[7], [8] compared to >200 mV loss for GaAs on Si. However, relative to GaAs, there have been limited studies to quantify GaInP on Si cell performance as a function of TDD or cell design [15], [16]. A detailed study of GaInP cells versus TDD would greatly inform the optimal design for III-V on Si MJSCs.

The standard GaInP cell design is the FJ  $n^+/p$  or  $p^+/n$  cell, which consists of a thin  $n^+$ - or  $p^+$ -emitter on a thick *p*- or *n*-type base to maximize photocarrier generation and collection near the space charge region (SCR). However, to date, the highest efficiency GaInP cells lattice-matched on GaAs have used a rear-heterojunction (RHJ) *n*-on-*p* design, in which a thick (>800 nm), lightly doped ( $1\text{--}5 \times 10^{17} \text{ cm}^{-3}$ ) *n*-type GaInP absorber forms a junction on top of *p*-AlGaInP [17], [18], [19]. Due to their junction placement far from the highest photocarrier region, RHJ cells require high minority carrier diffusion length to achieve similar EQE to FJs, and may be particularly sensitive to defects that lower diffusion length. As an example, rear-junction GaAs<sub>0.75</sub>P<sub>0.25</sub> 1J cells on GaAs showed improved  $V_{OC}$  over FJ cells but also lower QE due to the higher sensitivity of the rear-junction cell to diffusion length [20]. However, since minority hole mobilities in GaInP are several times lower than in GaAs or GaAsP, the  $V_{OC}$  and QE of GaInP rear-junction cells may be more resilient to dislocations [15], motivating a comparative study of FJ and RHJ GaInP cells on Si.

In this work, we first report lifetime studies with time-resolved photoluminescence (TRPL) on *n*-GaInP and *p*-GaInP double heterostructures (DHs) grown on both GaAs and Si, obtaining a peak *n*-GaInP lifetime on Si of 11.7 ns. Next, the performance of GaInP FJ and RHJ cells on GaAs and Si were compared. FJ cells had superior carrier collection on both substrates due to superior junction placement, while RHJs had superior  $V_{OC}$  and minimal  $V_{OC}$  degradation on Si due to the use of the *n*-type absorber. Finally, we propose paths to boost the carrier collection of RHJs to leverage their superior absorber material quality.

## II. METHODS

All DHs and solar cells were grown by solid-source molecular beam epitaxy (MBE) using a Veeco Mod Gen II MBE system. The dopants used were Si for *n*-type layers and Be for *p*-type

Sputtered SiO <sub>2</sub>			
Contact	n <sup>+</sup> -GaAs	Sputtered TiO <sub>2</sub>	
Window	n-AlInP	$1 \times 10^{18} \text{ cm}^{-3}$	20 nm
Emitter	n-GaInP	$2 \times 10^{18} \text{ cm}^{-3}$	50 nm
Base	p-GaInP	$1 \times 10^{17} \text{ cm}^{-3}$	710 nm
BSF	p-GaInP	$2 \times 10^{18} \text{ cm}^{-3}$	50 nm
BSF	p-AlInP	$2 \times 10^{18} \text{ cm}^{-3}$	50 nm
Contact	p <sup>+</sup> -GaAs	$7 \times 10^{18} \text{ cm}^{-3}$	150 nm
<b>p-GaAs or GaAs/Si (001)</b>			

(a)

Contact	n <sup>+</sup> -GaAs		
Window	n-AlInP	$1 \times 10^{18} \text{ cm}^{-3}$ (w/ $\delta$ spikes)	20 nm
Emitter	n-GaInP	$1 \times 10^{17} \text{ cm}^{-3}$	810 nm or 500 nm
BSF	p-AlGaInP	$1 \times 10^{17} \text{ cm}^{-3}$	100 nm
Buffer	p-AlGaAs	$2.4 \times 10^{18} \text{ cm}^{-3}$	100 nm
Contact	p <sup>+</sup> -GaAs	$7 \times 10^{18} \text{ cm}^{-3}$	500 nm
<b>p-GaAs or GaAs/Si (001)</b>			

(b)

Fig. 2. Growth structures for (a) FJ and (b) RHJ GaInP cells grown on *p*-GaAs and GaAs/Si (001).

layers. GaAs was grown on GaP/Si (001) from NAsP<sub>III-V</sub> GmbH to form GaAs/Si templates, and samples were subsequently cogenerated on GaAs substrates and GaAs/Si. GaInP layers were grown at a substrate temperature of 460 °C and a growth rate of 0.5  $\mu\text{m/h}$ . The *n*-type and *p*-type GaInP DHs, given in Fig. 1, had a 500-nm GaInP absorber layer with doping of  $1 \times 10^{17} \text{ cm}^{-3}$ , the same doping as the main absorber regions for the RHJ and FJ cells. The *n*-GaInP and *p*-GaInP DHs used 2.3 eV *n*-Al<sub>0.52</sub>In<sub>0.48</sub>P (hereafter AlInP) and 2.2 eV *p*-Al<sub>0.24</sub>Ga<sub>0.28</sub>In<sub>0.48</sub>P (hereafter AlGaInP) for the barrier layers to match the window and back-surface field (BSF) passivating layers, respectively, in the solar cells.

The layer structures for GaInP FJ and RHJ solar cells are given in Fig. 2. The growth structure of the GaAs/Si template varied for the cells and DHs: for the FJs, we grew a 3.64  $\mu\text{m}$  GaAs<sub>*y*</sub>P<sub>1-*y*</sub> step-graded buffer prior to GaAs growth, while for the RHJs and DHs, we utilized a GaAs/Si template design consisting of 1.8–2.6  $\mu\text{m}$  GaAs buffer layers with inserted InGaAs dislocation filter layers and thermal cycle annealing to reduce TDD [21], [22]. However, while buffer designs differed, the primary interest

in this work is cell performance as a function of TDD rather than of specific buffer design. From top to bottom, the FJ cells consisted of a 20 nm AlInP window ( $n = 1 \times 10^{18} \text{ cm}^{-3}$ ), a 50 nm  $n$ -GaInP emitter ( $n = 2 \times 10^{18} \text{ cm}^{-3}$ ), a 710 nm  $p$ -GaInP base ( $p = 1 \times 10^{17} \text{ cm}^{-3}$ ), and finally both a 50 nm  $p$ -GaInP BSF ( $p = 2 \times 10^{18} \text{ cm}^{-3}$ ) and AlInP BSF ( $p = 2 \times 10^{18} \text{ cm}^{-3}$ ) for rear surface passivation. The RHJ cells consisted of a 20 nm  $n$ -AlInP window ( $n = 5 \times 10^{18} \text{ cm}^{-3}$ ), a 500-810 nm  $n$ -GaInP emitter ( $n = 1 \times 10^{17} \text{ cm}^{-3}$ ), and a 100 nm  $p$ -AlGaInP BSF ( $p = 1 \times 10^{17} \text{ cm}^{-3}$ ), with the junction at the emitter/BSF interface. The RHJ AlInP window had  $5\times$  higher doping than FJs to improve front-surface passivation, which was vital for high-performance GaInP RHJs [19], and this higher doping was achieved by the addition of four delta-doped layers of Si (0.01 monolayers each). Compared to the  $n$ -AlInP barriers for the  $n$ -GaInP DH, the  $n$ -AlInP window on the RHJs is much thinner, so higher doping was needed to provide a comparable level of surface passivation.

A two-layer antireflection coating (ARC) of  $\text{TiO}_x/\text{SiO}_x$  was sputtered onto the FJs, while no ARC was applied to the RHJs. We performed postgrowth rapid thermal annealing (RTA) to improve the phosphide material quality of both DHs and cells, as reported previously [19], with temperatures of 750–1000 °C and annealing times of 10–120 s. Cells were processed using standard lithography and metal deposition techniques, with device dimensions of 1.1 mm  $\times$  1.1 mm; metal contacts were deposited on the top surfaces of the  $n^+$ -GaAs and  $p^+$ -GaAs contact layers shown in Fig. 2. To measure TDD, we used cathodoluminescence (CL) for DHs and electron beam-induced current (EBIC) mapping for processed solar cell devices.

DH lifetimes were measured by TRPL using a pulsed super-continuum laser under low-level injection conditions ( $<5 \times 10^{15} \text{ cm}^{-3}$  carriers) with a single photon detection module (ID Quantique, model No. id 100-20). For this setup, measurements for accurate TRPL lifetimes ( $\tau_{\text{TRPL}}$ ) were limited to  $\tau_{\text{TRPL}} > 1.3 \text{ ns}$  due to overlap with the system response function. For solar cells, lighted current-voltage (LIV) measurements were obtained under approximate AM1.5G conditions using an ABET 10 500 solar simulator. EQE and reflectance were measured with a PV Measurements QEX7 system to obtain internal quantum efficiency (IQE) by the equation  $\text{IQE} = \text{EQE}/(1-R)$ . Finally, we extract the dark current parameters  $J_{01}$  and  $J_{02}$  from Suns- $V_{oc}$  and dark current-voltage measurements.

### III. RESULTS AND DISCUSSION

The  $\tau_{\text{TRPL}}$  value of the  $n$ -GaInP DH was much higher than  $p$ -GaInP for growth on both GaAs and GaAs/Si, as shown in Fig. 3(a). The TDD for the DH structures ranged from  $8.0\text{--}9.4 \times 10^6 \text{ cm}^{-2}$ , with a representative CL image for the  $n$ -GaInP DH in Fig. 4(a). Remarkably, the  $n$ -GaInP DH grown on GaAs/Si experiences only a modest degradation in  $\tau_{\text{TRPL}}$  from 14.6 to 11.7 ns. The mechanisms of higher nonradiative recombination in  $p$ -GaInP DHs are uncertain; a  $\sim 10\times$  higher surface recombination velocity (SRV) has been measured for  $p$ -GaInP DHs compared to  $n$ -GaInP DHs [23], but bulk lifetime is still several times lower after accounting for SRV.  $\tau_{\text{TRPL}}$  of

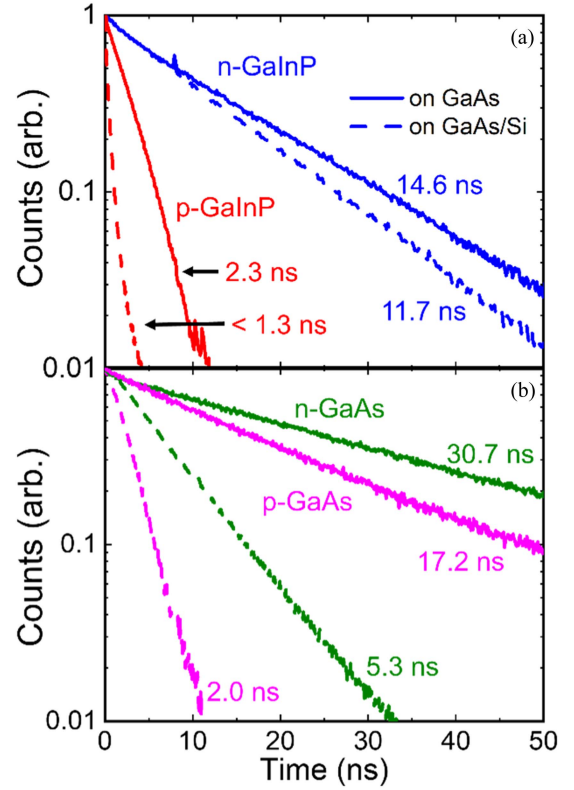


Fig. 3. TRPL decay curves on GaAs substrates (solid) and GaAs/Si templates (dashed) for (a) GaInP DHs and (b) GaAs DHs. The  $n$ -GaInP DH shows minimal lifetime degradation on GaAs/Si.

the  $p$ -GaInP DH decreased from 2.3 ns on GaAs to  $< 1.3 \text{ ns}$  on GaAs/Si;  $\tau_{\text{TRPL}}$  of the  $p$ -GaInP DH on GaAs/Si was too low to be accurately measured with the setup due to overlap with the system response function. For comparison purposes, we also grew  $n$ - and  $p$ -GaAs DHs on GaAs and GaAs/Si with the same thickness, doping, and TDD as the GaInP DHs.  $\tau_{\text{TRPL}}$  of the  $n$ -GaAs DH degraded from 30.7 to 5.3 ns for growth on GaAs/Si ( $5.7\times$  decrease), while the lifetime of the  $p$ -GaAs DH degraded from 17.2 to 2 ns ( $8.6\times$  decrease) for growth on GaAs/Si. The minority carrier diffusivity in  $n$ -GaInP ( $\sim 2 \text{ cm}^2/\text{s}$ ) is much lower than that in  $n$ -GaAs and  $p$ -GaAs ( $\sim 8$  and  $80 \text{ cm}^2/\text{s}$ , respectively), leading to its higher dislocation tolerance.

Next, a pair of RHJ solar cells were cogrown on GaAs (RHJ1) and GaAs/Si at a TDD of  $1.0 \times 10^7 \text{ cm}^{-2}$  (RHJ2) with  $n$ -GaInP emitter thickness of 810 nm, while a third RHJ was separately grown on GaAs/Si at a high TDD of  $2.7 \times 10^8 \text{ cm}^{-2}$  (RHJ3), with emitter thickness of 500 nm. For FJs, two cells were cogrown on GaAs (FJ1) and GaAs/Si at TDD of  $2.7 \times 10^7 \text{ cm}^{-2}$  (FJ2). Fig. 4(b)–(d) shows representative EBIC images for all three cells grown on GaAs/Si; each black dot is a threading dislocation, and the absence of black lines indicates there are no misfit dislocations in the active region of the cells.

The IQE spectra of FJ cells were insensitive to TDD, with virtually identical spectra (see Fig. 5) and IQE-derived  $J_{\text{SC,IQE}}$  values  $J_{\text{SC,IQE}} > 14.0 \text{ mA/cm}^2$  under the AM1.5G spectrum (see Table I), on par with those reported in prior epitaxial tandems on Si [6], [7], [9], [14]. In contrast, the best  $J_{\text{SC,IQE}}$  for the RHJs

TABLE I  
DESCRIPTION AND FIGURES OF MERIT FOR GAINP SOLAR CELLS IN THIS WORK

FJ (w/ ARC)	TDD (cm <sup>-2</sup> )	GaInP thickness (nm)	Peak IQE (%)	IQE-derived J <sub>sc</sub> (mA/cm <sup>2</sup> )	V <sub>oc</sub> (V)	J <sub>sc</sub> (mA/cm <sup>2</sup> )	FF (%)	η (%)	J <sub>02</sub> (A/cm <sup>2</sup> )
FJ1	<5.0 × 10 <sup>3</sup>	810	91.9	14.0	1.299	12.9	78.1	13.1	2.1 × 10 <sup>-13</sup>
FJ2	2.7 × 10 <sup>7</sup>	810	92.8	14.3	1.216	13.4	74.8	12.2	8.0 × 10 <sup>-13</sup>
<b>RHJ (no ARC)</b>									
RHJ1	<5.0 × 10 <sup>3</sup>	810	57.8	9.3	1.333	6.2	79.5	6.5	2.4 × 10 <sup>-14</sup>
RHJ2	1.0 × 10 <sup>7</sup>	810	65.9	10.8	1.292	7.4	78.3	7.4	1.0 × 10 <sup>-13</sup>
RHJ3	2.7 × 10 <sup>8</sup>	500	38.3	5.8	1.223	4.0	73.0	3.5	1.9 × 10 <sup>-13</sup>

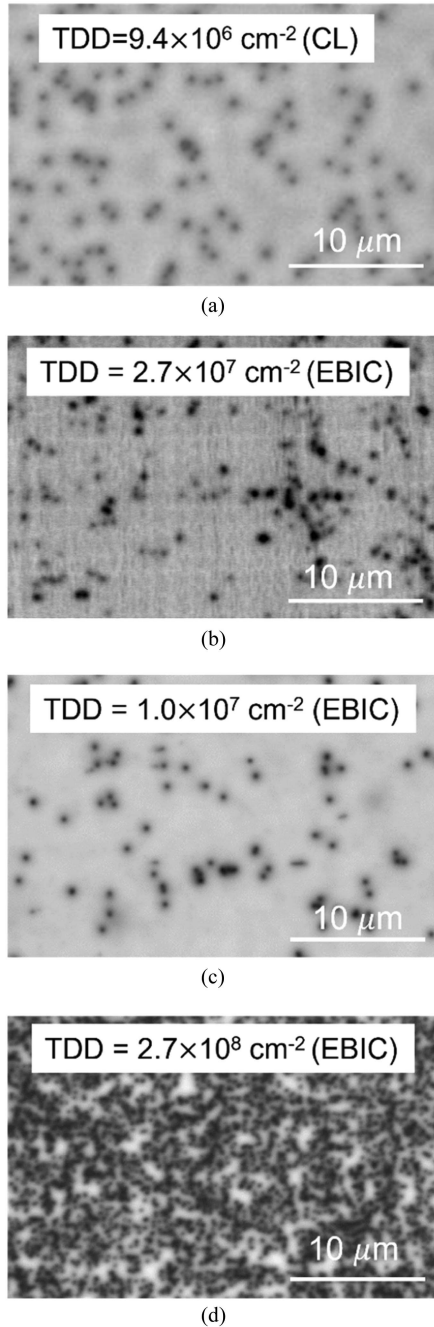


Fig. 4. (a) Representative CL image of *n*-GaInP DH on Si and (b)–(d) representative EBIC images for FJ2, RHJ2, and RHJ3. For both CL and EBIC images, each black dot represents a thread.

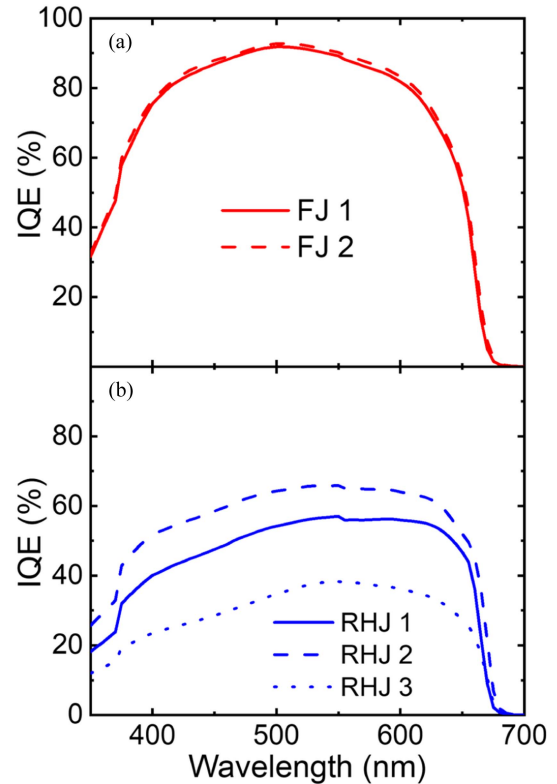


Fig. 5. IQE curves of (a) FJ and (b) RHJ cells.

was in RHJ2 with a value of only 10.8 mA/cm<sup>2</sup>. In addition, RHJ1 had worse IQE than RHJ2 despite having superior bulk material quality as indicated by the higher  $V_{OC}$  (see Table I). The low IQE of RHJ1 on GaAs indicates contributing factors other than TDD to poor carrier collection in these cells. We believe one significant cause of the lower IQE of RHJ1 is higher front SRV, to which rear-junction cells are known to be highly sensitive [19], [20]. This theory is supported by the fact that  $J_{01}$ , which depends on both bulk quality and SRV [24], was 2.8× higher in RHJ1 than RHJ2. The window design may need further improvements beyond the additional delta-doping layers to provide reliable front-surface passivation of RHJs.

We next used Hovel modeling of IQE [25] to quantify the performance limitation in the RHJs and optimize the absorber thickness. From modeling, the FJ base and RHJ emitter of the moderate TDD cells (FJ2 and RHJ2) had comparable minority

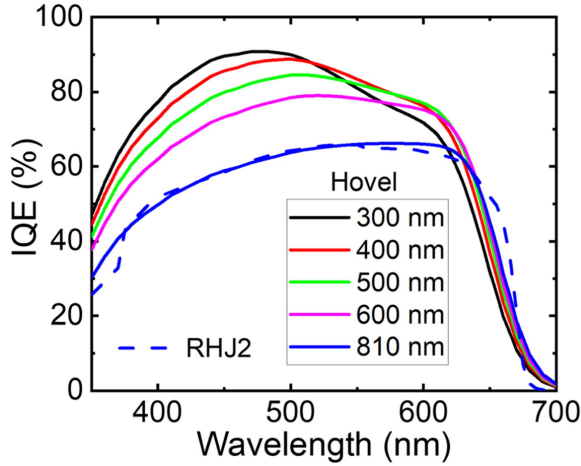


Fig. 6. Hovel IQE of RHJ design (solid) as a function of emitter thickness using fitted diffusion length of 700 nm from RHJ2 (dotted line).

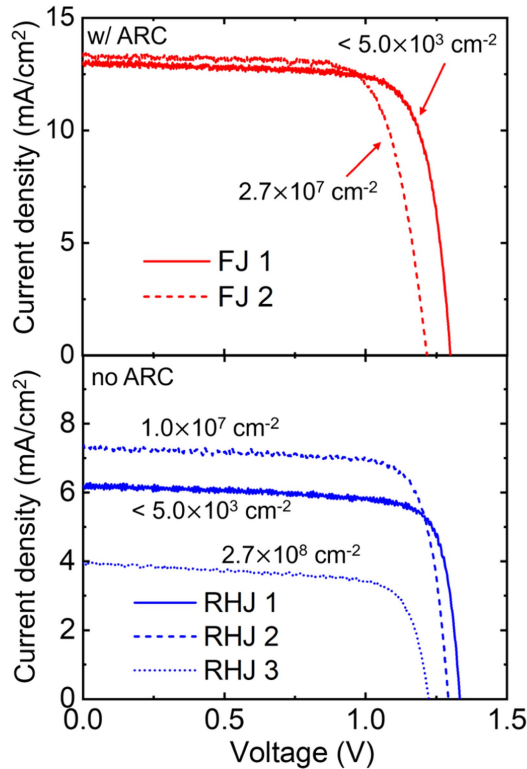


Fig. 7. LIV curves of FJ cells (w/ ARC) and RHJ cells (no ARC).

carrier diffusion lengths  $L_{n,p}$  of  $\sim 700$  nm. The similar diffusion length is evidence of greater carrier lifetime in the RHJ emitter, given the much lower minority hole mobility. However, the junction placement far from the top surface, where most carrier generation occurs, resulted in worse IQE at similar  $L_{n,p}$ . Next, modeling IQE as a function of RHJ emitter thickness (see Fig. 6),  $J_{SC,IQE}$  was optimized at an emitter thickness of 400 nm, with a value of  $13.4 \text{ mA/cm}^2$  that approaches the FJ value as well as  $J_{SC}$  values in literature.

The RHJ cells also had lower efficiency from LIV measurements (see Table I and Fig. 7) due to the low  $J_{SC}$  of the RHJs,

which stems from both the lack of ARC and diminished IQE. However, the RHJ2 with a TDD of  $1.0 \times 10^7 \text{ cm}^{-2}$  shows  $V_{OC} = 1.292 \text{ V}$ , comparable to the nearly dislocation-free FJ1 at  $1.299 \text{ V}$ . In addition, RHJ3 has a  $V_{OC}$  of  $1.223 \text{ V}$ , greater than the  $1.216 \text{ V}$  of FJ2 despite having  $10\times$  higher TDD and being in a regime where carrier lifetime is dominated by nonradiative recombination at threading dislocations. These high  $V_{OC}$  values for the RHJs are especially notable given that their low  $J_{sc}$  values will also lower the  $V_{OC}$ .

$V_{OC}$  comparisons for the FJ and RHJ cells are complicated by their dependence on  $J_{sc}$ ,  $J_{01}$ , and  $J_{02}$  as given by solving the double-diode model at the open-circuit condition

$$J_{sc} = J_{01} \exp\left(\frac{qV_{OC}}{kT}\right) + J_{02} \exp\left(\frac{qV_{OC}}{2kT}\right) \quad (3)$$

where  $k$  is the Boltzmann constant,  $T$  is the temperature, and  $q$  is the unit charge.  $J_{01}$  and  $J_{02}$  are dependent on the bulk carrier lifetime, while  $J_{01}$  is additionally affected by SRV. The effect of SRV is notable when comparing RHJ1 to RHJ2, in which the higher  $J_{01}$  of RHJ1 accounts for  $\sim 26 \text{ mV}$  of  $V_{OC}$  loss relative to RHJ2. However, for a more objective comparison of bulk material quality in the different solar cells as a function of TDD, we will primarily compare  $J_{02}$  values. The  $J_{02}$  dark current, which stems from recombination in the SCR, is approximated by

$$J_{02} = \frac{qWn_i}{2\tau} \quad (4)$$

where  $W$  is the depletion region width,  $n_i$  is the intrinsic carrier concentration, and  $\tau$  is the minority carrier lifetime. The  $V_{OC}$  due to  $J_{02}$  dark current is then given by [12]

$$V_{OC} = \frac{2kT}{q} \ln\left(\frac{J_{SC}}{J_{02}}\right). \quad (5)$$

The experimental  $J_{02}$  values are given in the right-most column of Table I. For both FJs and RHJs,  $J_{02}$  increased by  $\sim 4\times$  when comparing the cells on GaAs (FJ1 and RHJ1) to the cells on Si at moderate TDD (FJ2 and RHJ2), with a decrease in calculated  $V_{OC}$  of  $69.2 \text{ mV}$  and  $74.5 \text{ mV}$  for FJs and RHJs, respectively. From RHJ2 to RHJ3, the  $J_{02}$  increases by a further  $1.9\times$ , with a decrease in  $V_{OC}$  of only  $32 \text{ mV}$ . The experimental  $J_{02}$  values for the cells grown on Si (FJ2, RHJ2, and RHJ3) were  $8.0 \times 10^{-13}$ ,  $1.0 \times 10^{-13}$ , and  $1.9 \times 10^{-13} \text{ A/cm}^2$ , respectively, showing much lower  $J_{02}$  values for RHJs even with a  $10\times$  higher TDD in RHJ3. The greatly reduced  $J_{02}$  of both RHJs may be due to both a smaller depletion region width and higher lifetime in the  $n$ -GaInP absorber. One assumption for the RHJs is that the contribution of the  $2.2 \text{ eV}$  AlGaInP BSF to  $J_{02}$  is minimal, since the  $300 \text{ meV}$  higher bandgap leads to almost 3 orders of magnitude lower intrinsic carrier concentration. With this assumption, the effective SCR width for the RHJ cells is approximately  $109.1 \text{ nm}$  (depletion on the GaInP emitter only), while the total SCR width of the FJ is  $164.7 \text{ nm}$ , including both the emitter and base contributions. This difference could approximately account for a  $1.5\times$  drop in the  $J_{02}$ , while the experimental  $J_{02}$  drops for RHJ2 and RHJ3 are  $8\times$  and  $4.2\times$ , respectively. Therefore, superior lifetime in the  $n$ -GaInP region

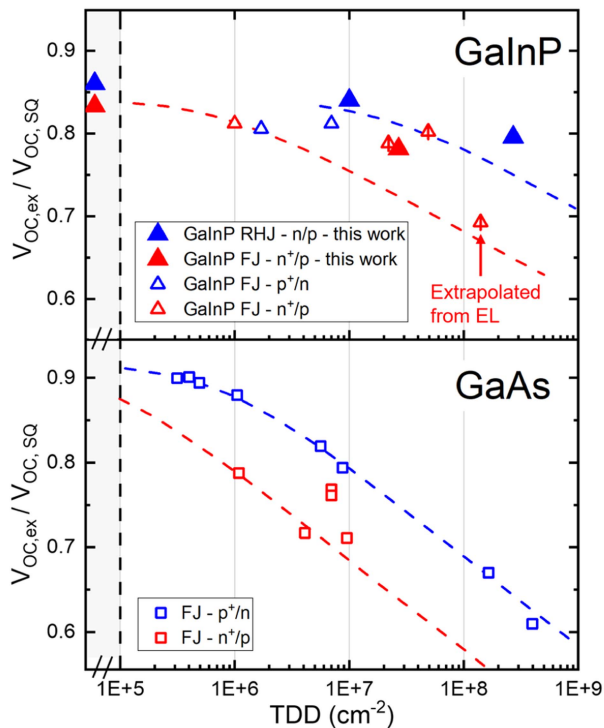


Fig. 8.  $V_{OC}$  fraction of GaInP and GaAs cells as a function of TDD. Grey bars on the left are for growth on lattice-matched GaAs substrates. GaAs cells (hollow squares) are from [12] and [13] whereas GaInP cells (hollow triangles) are from [7], [8], [16], [27] and coplotted with cells from this work (solid triangles). The hollow triangles with a bisecting vertical line were extrapolated from EL measurements assuming  $n = 2$  ideality factor. Dotted lines are calculated Yamaguchi degradation curves from [16]. GaInP RHJs and  $p^+/n$  GaInP FJs showed the least degradation among the cell types.

of the RHJs should also contribute significantly to the reduced  $J_{02}$  of cells on GaAs/Si, as promised by the TRPL study. If  $J_{sc}$  of RHJ3 were boosted to similar levels as FJ2, the  $V_{OC}$  value would be  $\sim 70$  mV greater than FJ2 rather than only 7 mV higher.

The high  $V_{OC}$  retention of RHJ cells on GaAs/Si compared to FJ cells on GaAs/Si correlates well with both existing literature and prior models of  $V_{OC}$  as a function of TDD. Fig. 8 summarizes literature data for GaInP and GaAs cells on Si as a function of TDD, plotted in terms of a  $V_{OC}$  fraction  $V_{OC,ex}/V_{OC,sq}$  where  $V_{OC,ex}$  is the experimental  $V_{OC}$  value and  $V_{OC,sq}$  is the Shockley-Queisser value under AM1.5G spectrum [26].  $V_{OC,sq}$  was adjusted for each GaInP device according to their  $E_g$  values, which ranged from 1.83–1.90 eV. Several of the GaInP  $n^+/p$  FJ data points were extrapolated from EL subcell measurements of GaInP from a many-suns intensity down to the 1-sun condition (hollow triangles with vertical line) [7], [8]. The extrapolated 1-sun  $V_{OC}$  values assume an  $n = 2$  ideality factor, which should dominate with high TDD [12]. Finally, the modeled  $V_{OC}$  versus TDD degradation curves (dotted lines) from Andre [16] used Yamaguchi’s lifetime model for  $V_{OC}$  degradation for both  $n^+/p$  and  $p^+/n$  polarities of GaInP and GaAs FJ solar cells. Given the wide variability in experimental lattice-matched solar cell performance, comparisons between the cells are most apt at larger TDD values where performance is dominated by  $\tau_{TDD}$  and the minority carrier mobility of the absorber regions.

From in-house Yamaguchi modeling of  $V_{OC}$  versus TDD, FJ  $n^+/p$  cells start to become dominated by threading dislocations (defined as a 10 mV loss of  $V_{OC}$ ) at  $TDD = 1 \times 10^7 \text{ cm}^{-2}$ , while the  $p^+/n$  FJ and  $n/p$  RHJ cells do not become TDD-dominated until  $TDD = 7 \times 10^7 \text{ cm}^{-2}$ . In these elevated TDD ranges, Fig. 8 illustrates the resilience of the RHJ cells in this work compared to FJ cells. In addition, the comparison between GaInP and GaAs highlights the steep drop in the  $V_{OC}$  of GaAs cells as a function of TDD. Our results clearly demonstrate the low  $V_{OC}$  degradation of RHJ GaInP cells, motivating further work, particularly on improving the IQE of RHJ cells on Si.

#### IV. CONCLUSION

In this work, FJ GaInP cells on Si showed significantly higher current collection than RHJs, with  $J_{sc}$  values comparable to the best GaInP on Si subcells in the literature, and no  $J_{sc}$  degradation from GaAs to Si substrates. However, the high dislocation tolerance of RHJ cells relative to FJ, as shown by greater  $V_{OC}$  and reduced  $J_{02}$ , even at  $TDD > 1 \times 10^8 \text{ cm}^{-2}$ , also motivates further efforts to study RHJ cells for MJSC applications. For future work, annealing conditions on GaAs/Si with lower temperature (700–750 °C) and longer time (10–60 min) may improve phosphide quality in the cells over RTA. In addition, an optimized design with a thinner absorber of  $\sim 400$  nm, similar to GaInP cells already used for epitaxial III–V/Si in the literature, as well as more reliable front-surface passivation, should significantly increase the IQE of the RHJ cells towards FJ values, enabling RHJ cells for current matching on III–V/Si MJSCs.

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