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Alexandra Bothwell, Jake Wands, Michael Miller, Ana Kanevce, Stefan Paetel, et al.. Nonradiative Recombination Dominates Voltage Losses in Cu(In,Ga)Se<sub>2</sub> Solar Cells Fabricated using Different Methods. Solar RRL, 2023, 7 (11), pp.2300075. 10.1002/solr.202300075 . hal-04101097

**HAL Id: hal-04101097**

**<https://hal.science/hal-04101097v1>**

Submitted on 31 Jul 2024

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# **Non-Radiative Recombination Dominates Voltage Losses in Cu(In,Ga)Se<sub>2</sub> Solar Cells Fabricated Using Different Methods**

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Keywords: solar cells, Cu(In,Ga)Se<sub>2</sub>, voltage losses, non-radiative recombination

Voltage losses reduce the photovoltaic conversion efficiency of thin-film solar cells, and are a primary efficiency limitation in Cu(In,Ga)Se<sub>2</sub>. This work presents a voltage loss analysis of

Cu(In,Ga)Se<sub>2</sub> solar cells fabricated at three institutions with variation in process, bandgap, absorber structure, post deposition treatment (PDT), and efficiency. Non-radiative voltage losses due to Shockley-Read-Hall (SRH) charge carrier recombination dominate and constitute >75% of the total compared to <25% from radiative voltage losses. The radiative voltage loss results from non-ideal absorption and carriers in band tails that stem from local composition-driven potential fluctuations. We show that significant bulk lifetime improvements are achieved for all alkali PDT processed absorbers, chiefly associated with reductions in non-radiative recombination. Primary voltage loss contributions—radiative and non-radiative—change little across fabrication processes, but variation in sub-mechanisms—bulk lifetime, net acceptor concentration, and interface recombination—differentiate non-radiative loss pathways in this series of solar cells.

## 1. Introduction

Cu(In,Ga)Se<sub>2</sub> (CIGS)-based thin film solar cells hold significant promise due to the tunable, direct bandgap, high absorption coefficient, thin layers, flexible and rigid substrate applications, processing options, and consistent efficiency increases.<sup>[1-3]</sup> Photovoltaic conversion efficiencies have reached 23.4% in small-area CIGS solar cells,<sup>[4]</sup> and significant improvements have originated from absorber composition changes and heavy alkali post-deposition treatments (PDTs).<sup>[5-13]</sup>

Absorber energy gap and electron affinity can be controlled by the Ga/(Ga+In) (GGI) ratio, which offers two benefits. First, increases in GGI widen the absorber bandgap which raises the maximum achievable open circuit voltage ( $V_{OC}$ ) and efficiency of the device.<sup>[14]</sup> Second, GGI grading is used to create a “notched” graded bandgap in which the bandgap is increased at both the front and rear portions of the absorber and a bandgap minimum is maintained in the front half of the absorber.<sup>[6]</sup> The front-side bandgap increase reduces front interface hole recombination and back-side grading reduces back interface electron recombination such that  $V_{OC}$  improvements up to 100 mV are achievable with a change in GGI ~0.5.<sup>[15, 16]</sup> However, voltage losses increase for GGI > 0.4 in the minimum bandgap region such that efficiency improvements are limited.<sup>[17-19]</sup> This can be mitigated in part through silver-alloyed ACIGS devices ((Ag,Cu)(In,Ga)Se<sub>2</sub>), which have demonstrated higher  $V_{OC}$  and efficiency with a wider bandgap.<sup>[18, 20-22]</sup>

Heavy alkali PDTs, including CsF, RbF, and KF, have led to notable efficiency increases, in large part due to improved  $V_{OC}$ .<sup>[8-13]</sup> This has been related to improvements in the absorber

bulk, specifically the accumulation of heavy alkalis which leads to reduction of charged defects at grain boundaries.<sup>[8]</sup>

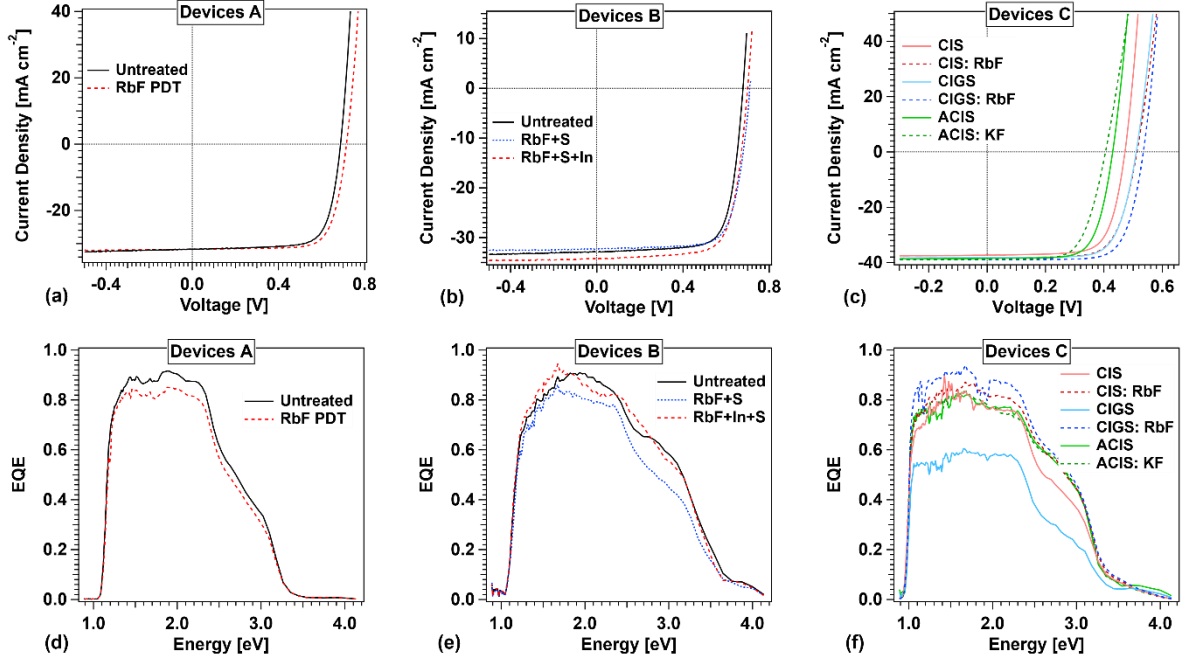
Voltage losses have been discussed in the literature in the context of GGI and heavy alkalis in CIGS devices, however, most studies have investigated voltage losses in a limited set of device structures and primarily through the lens of external radiative efficiency, Urbach energies, optical losses, or defects.<sup>[8, 23, 24]</sup> Studies that analyzed a diverse set of devices did not include detailed voltage loss assessment.<sup>[2]</sup> As summarized by Kirchartz and Rau,<sup>[25]</sup> a majority of the losses in CIGS are non-radiative recombination losses.

In this work, we characterize voltage losses and mechanisms across devices fabricated at three institutions with variations in bandgap (1.0–1.19 eV), absorber structure (Ga inclusion, Ag-alloying), PDT (RbF and KF treatments), and efficiency (10.4% – 17.5%). Across all devices, voltage losses were dominated by non-radiative recombination—which contributed >75% of the total—compared to <25% contribution from radiative voltage loss. Ga inclusion reduced voltage losses while Ag-alloying did not have a consistent effect. Generally, PDTs decreased voltage loss through reduced non-radiative recombination, specifically by increased minority carrier lifetime. In contrast, PDTs did not demonstrate a consistent effect on radiative voltage loss. Therefore, further reductions in radiative losses will likely require fabrication advances beyond PDTs. This work emphasizes that the dominant voltage loss mechanism in CIGS devices, non-radiative recombination, and the bulk lifetime-induced improvement after PDT are fabrication agnostic.

## 2. Results

### 2.1. Device Performance, Bandgaps, and Radiative Voltage

$V_{OC}$  is fundamentally limited by the device bandgap ( $E_g$ ),<sup>[26]</sup> and the difference between  $E_g$  and measured  $V_{OC}$  is often described as the voltage deficit.  $V_{OC}$  values were extracted from current density-voltage (J-V) measurements, given in **Figure 1(a-c)**, and all performance parameters are tabulated in Table 1. RbF-based PDTs increased  $V_{OC}$  across all manufacturers and absorber structures.  $V_{OC}$  reduction in the ACIS device compared to CIS device (devices C), regardless of PDT, and reported success of Ag-alloying in CIGS architectures<sup>[20-22]</sup> may suggest that Ag-alloying may be better suited for Ga-containing absorbers. Devices without Ga (CIS and ACIS) demonstrated the lowest device efficiencies and  $V_{OC}$ s, and we will show that the difference in voltage between Ga-containing and non-Ga devices is due to more than bandgap.



**Figure 1.** J-V curves of A (a), B (b), and C (c) devices. EQE spectra of A (d), B (e), and C (f) devices.

**Table 1.** Device Structures and Performance Parameters

Device	Absorber	PDT	$E_g$ [eV]	$V_{oc}$ [mV]	$J_{sc}$ [ $\text{mA cm}^{-2}$ ]	$FF$ [%]	$Eff.$ [%]
A	CIGS	none	1.15	688	31.7	74.6	16.3
		RbF	1.16	716	31.7	75.7	17.2
B	CIGS	none	1.14	678	32.8	74.3	16.5
		RbF+S	1.16	712	32.2	74.0	17.0
		RbF+In+S	1.14	700	34.2	73.2	17.5
C	CIS	none	1.00	472	37.3	71.9	12.7
		RbF	1.00	513	38.3	70.6	13.9
	CIGS	none	1.00	511	38.2	71.7	14.0
		RbF	1.00	535	39.0	73.4	15.3
	ACIS	none	1.00	430	38.5	70.5	11.7
		KF	1.00	406	38.7	66.0	10.4

External quantum efficiency (EQE) spectra, given in Figure 1(d-f) were used to quantify  $E_g$  in all devices according to the method outlined by Rau et al.<sup>[27]</sup> It submits that the shape of the  $EQE(E)$  derivative at the band edge is described by a distribution of bandgap energies ( $P(E_g)$ ) and is given by

$$P(E_g) = \frac{d}{dE} EQE(E). \quad (1)$$

The bandgap is then determined by:

$$E_g = \frac{\int_a^b E \cdot P(E_g) dE}{\int_a^b P(E_g) dE} \quad (2)$$

where  $a$  and  $b$  are the energies at which  $P(E_g)$  is half that of its maximum,  $P(a) = P(b) = \max(P(E_g))/2$ . The calculated bandgaps are given in Table 1.

Voltage loss is distinct from the voltage deficit,  $E_g - V_{OC}$ , because it quantifies the voltage difference in terms of the Shockley-Queisser (SQ) voltage,  $V_{OC,SQ}$ , the thermodynamic voltage limit.<sup>[26, 28]</sup> This description is especially appropriate for comparisons between devices with various bandgaps, typified here. Therefore, voltage loss in this work is taken to be  $V_{OC,SQ} - V_{OC}$ , also referred to as the  $V_{OC}$  voltage change. This difference combines radiative and non-radiative losses, and contact selectivity losses (contact selectivity losses are not considered here). Radiative losses are characterized by radiative voltage,  $V_{OC,rad}$ , calculated by:<sup>[29]</sup>

$$V_{OC,rad} = \frac{kT}{q} \ln \left( \frac{J_{SC}}{J_{0,rad}} + 1 \right) \quad (3)$$

where  $q$  is elementary charge,  $k$  is Boltzmann's constant, and  $T$  is temperature. The short circuit current density is

$$J_{SC} = q \int_0^\infty EQE(E) \cdot \phi_{sun}(E) dE \quad (4)$$

where  $\phi_{sun}(E)$  is the AM1.5 G solar spectrum photon flux. The radiative saturation current density,  $J_{0,rad}$  is given by:<sup>[25]</sup>

$$J_{0,rad} = q \int_0^\infty EQE(E) \cdot \phi_{BB}(E) dE \quad (5)$$

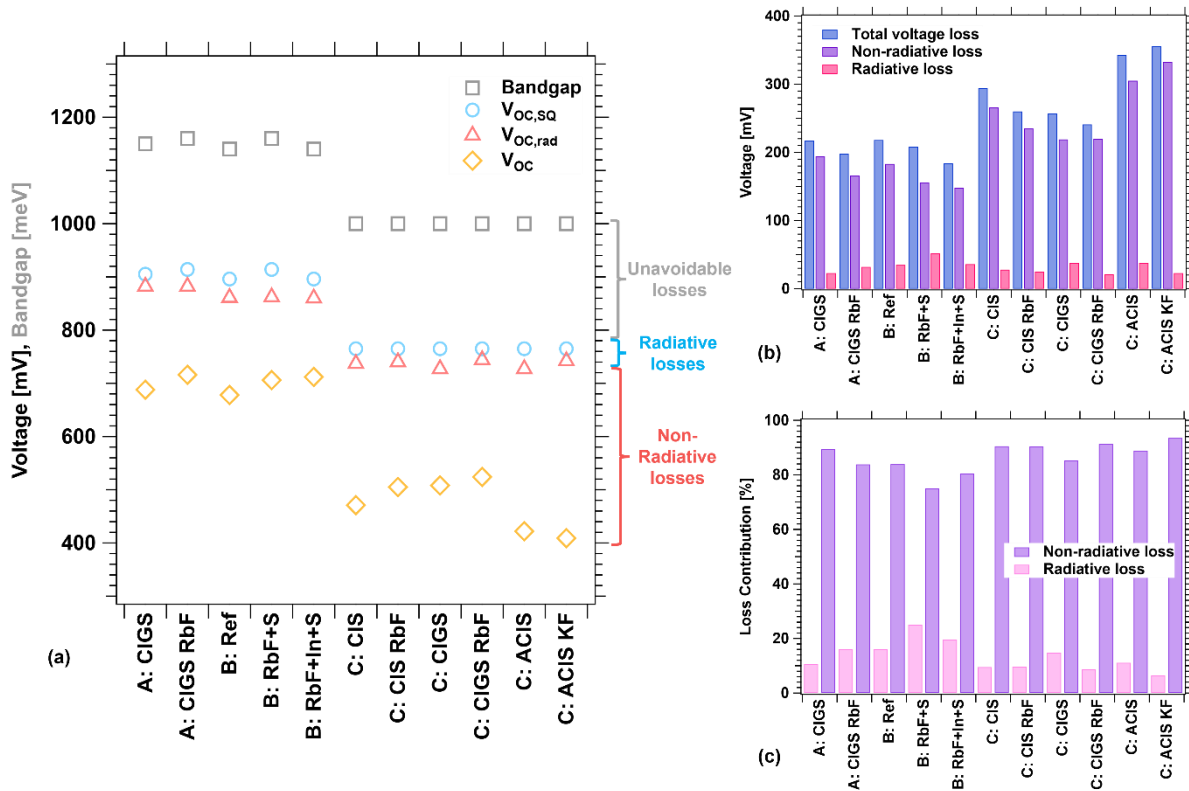
where  $\phi_{BB}(E)$  is the blackbody spectrum photon flux  $\phi_{BB} = \frac{2\pi}{c^2 h^3} \frac{E^2}{\left[ \exp\left(\frac{E}{kT}\right) - 1 \right]}$ ,  $h$  is Planck's constant and  $c$  is photon velocity in vacuum.  $V_{OC,rad}$  values, calculated from  $EQE(E)$  and Equations (3)-(5), are given in **Figure 2(a)**.

In the SQ-limit, complete absorption of photons with energy greater than or equal to the bandgap is assumed, i.e.  $EQE(E) = a(E) = 1$  for  $E \geq E_g$  and  $= 0$  for  $E < E_g$ , where  $a(E)$  is

energy-dependent absorptivity.  $V_{OC,SQ}$ , calculated using Equations (3)-(5) where the Heaviside step function is utilized for  $a(E)$ , are given in Figure 2(a).

Using the approach outlined above, each device is characterized by bandgap  $E_g$ , SQ voltage  $V_{OC,SQ}$ , radiative voltage  $V_{OC,rad}$  (Equation (3)), and device voltage  $V_{OC}$ . The total voltage losses  $V_{OC,SQ} - V_{OC}$  are shown in Figure 2(b). This difference includes voltage reduction due to sub-bandgap states (radiative losses  $V_{OC,SQ} - V_{OC,rad}$ ) and non-radiative Shockley-Read Hall (SRH) recombination ( $V_{OC,rad} - V_{OC}$ ), both also given in Figure 2(b). Auger recombination is not considered because it is an insignificant recombination mechanism at the typical injection levels used in this work.<sup>[30]</sup>

Figure 2(c) provides the percentage loss contribution from radiative and non-radiative voltage losses. Non-radiative SRH recombination was the dominant voltage loss mechanism in all devices regardless of architecture, bandgap, PDT, or performance, generating >75% of the total voltage loss. Concomitantly, non-radiative losses contributed <25% to the total. The non-radiative voltage changes are discussed in detail in section 2.2.



**Figure 2.** (a) Band gap ( $E_g$ ), SQ voltages, radiative voltages, and device voltages for solar cells in this study. Gray, blue, and red brackets identify unavoidable voltage losses ( $E_g - V_{OC,SQ}$ ), radiative losses ( $V_{OC,SQ} - V_{OC,rad}$ ), and non-radiative, SRH recombination losses ( $V_{OC,rad} - V_{OC}$ ), respectively. (b) Total voltage losses compared to radiative and non-radiative

losses and loss contribution percentages (c) show that non-radiative SRH recombination was the dominant loss category in all devices.

Radiative voltage losses stem from incomplete absorption and donor and acceptor distribution inhomogeneities at the nanometer scale (fluctuations). Incomplete absorption is particularly relevant in thin-film solar cells such as CIGS with absorbers  $\sim 2 \mu\text{m}$  and bandgap grading which leads to a non-ideal absorption edge. Fluctuations occur in many compound materials such as CIGS. Bandgap fluctuations describe spatial variations in the fundamental bandgap caused by compositional variations, stress, and stoichiometry. Electrostatic potential fluctuations describe distortions in the band structure caused by a distribution of charged states from structural defects, dopants, and impurities.<sup>[31]</sup> In the CIGS devices analyzed here, radiative voltage losses ranged from 23-52 mV, in agreement with the radiative loss range predicted by Wolter et al.<sup>[24]</sup> PDTs did not exhibit a consistent effect on radiative loss: devices A and B demonstrated increased radiative losses after PDT while devices C exhibited lower losses.

## 2.2. Non-Radiative Voltage Losses

Non-radiative SRH recombination originates from a combination of mechanisms. The relevant material and device characteristics which affect SRH recombination include minority carrier lifetime in the absorber ( $\tau_{bulk}$ ), net acceptor concentration ( $N_A$ ), back and front interface recombination velocities, and band bending. We analyze the SRH recombination losses given in Figure 2(b) to understand their origins. Time-resolved photoluminescence (TRPL) and capacitance-voltage (C-V) data are utilized for  $\tau_{bulk}$  and  $N_A$  determination, respectively, to estimate minority and majority carrier densities in CIGS solar cells.

**Figure 3**(a, b, and c) show low-injection TRPL data for devices A, B, and C. Effective lifetimes,  $\tau_{eff}$ , increased significantly (Table 2) in all PDT devices compared to their untreated counterparts. As is commonly used for CIGS,  $\tau_{eff}$  values were determined by single exponential fits to the TRPL decay tail, shown by gray fit lines in Figure 3(a, b, c). To quantify changes in  $\tau_{bulk}$ , voltage biased TRPL measurements were performed at low injection according to the method by Maiberg et al.<sup>[32]</sup> This method analyzes changes in  $\tau_{eff}$  with applied voltage bias ( $V$ ):

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_{b,n}} + \frac{1}{\tau_{b,p}} + \frac{\mu_n + \mu_p}{4VTd^2} (V_{bi} - V)^2. \quad (6)$$



$\tau_{b,n}$  and  $\tau_{b,p}$  are minority and majority bulk lifetimes respectively (corresponding to electrons and holes in CIGS),  $\mu_n$ , and  $\mu_p$  are minority and majority mobilities,  $V_T$  is thermal voltage, ( $\approx 25$  mV at room temperature),  $d$  is absorber thickness, and  $V_{bi}$  is built-in voltage. Changes in TRPL decay rates with voltage bias are induced by a change in the electric field, interface recombination, and electron extraction into the TCO at different voltage biases. Voltage-biased TRPL decay lifetimes ( $\tau_{eff}^{-1}$  vs. applied voltage) and 3-order polynomial fits to Equation (6) were used to determine minority carrier lifetimes. Examples are provided in the Supporting Information section. A few devices exhibited voltage-independent decays which can be caused by field effects, low doping, or non-standard transport mechanisms like trapping.<sup>[32, 33]</sup> In these cases,  $\tau_{eff}$  measured with forward-bias was used to approximate  $\tau_{bulk}$ .

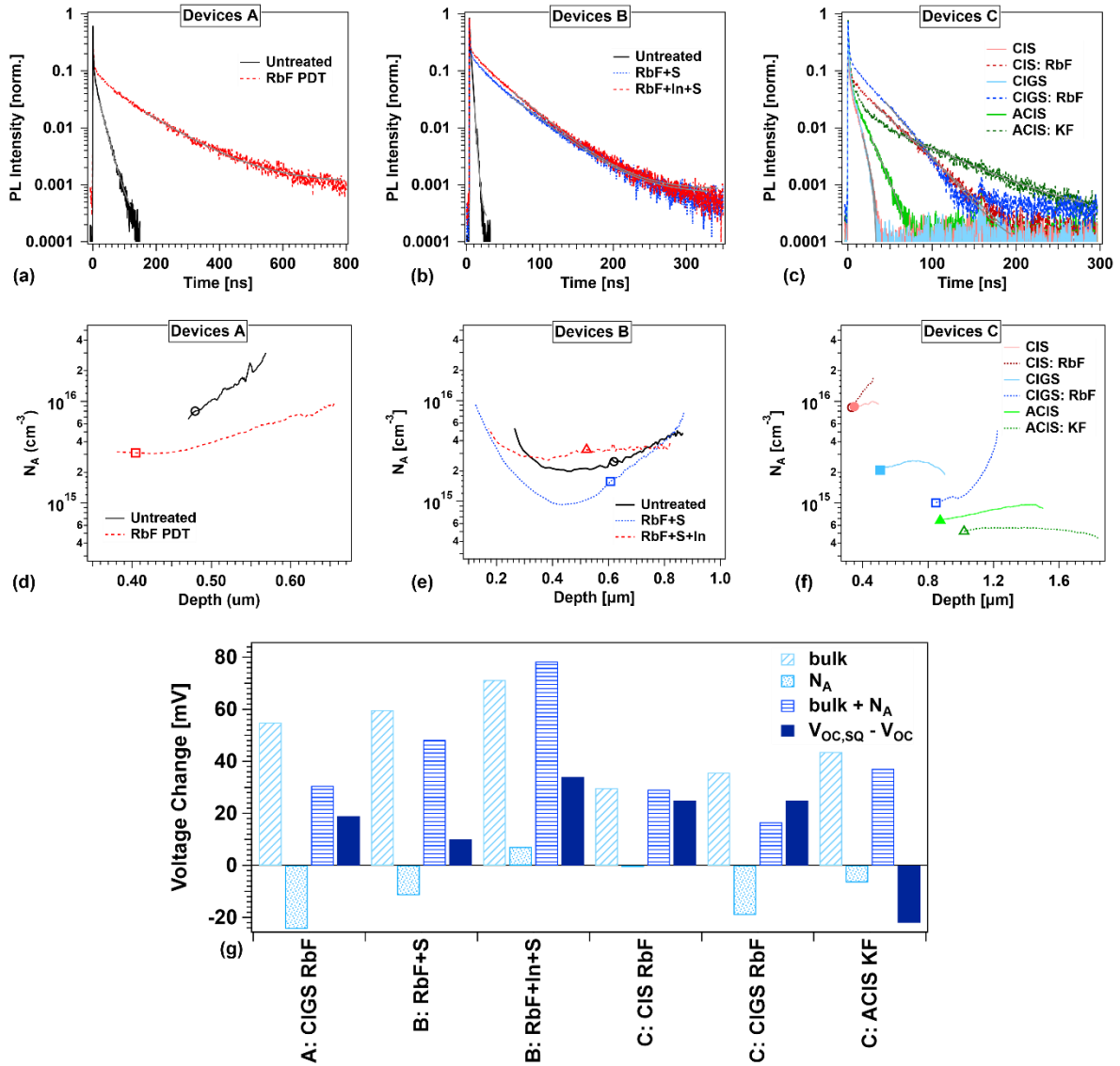
**Table 2.** PDT-Associated Non-Radiative Voltage Losses:  $V_{OC}$  voltage change ( $\Delta V_{OC,sq} - V_{OC}$ ), minority carrier lifetimes and associated voltage losses ( $\Delta V_{OC,bulk}$ ), and carrier concentrations and associated voltage losses ( $\Delta V_{OC,NA}$ ).

Device	Absorber	PDT	$\Delta V_{OC,sq} - V_{OC}$ [mV]	$\tau_{eff}$ [ns]	$\tau_{bulk}$ [ns]	$\Delta V_{OC,bulk}$ [mV]	$N_A$ [cm <sup>-3</sup> ]	$\Delta V_{OC,NA}$ [mV]
A	CIGS	none	19	19	19	55	$8.0 \times 10^{15}$	-24
		RbF		125	161		$3.1 \times 10^{15}$	
B	CIGS	none	27	3	14	60	$2.5 \times 10^{15}$	-11
		RbF+S		43	143		$1.6 \times 10^{15}$	
		RbF+In+S		35	224		$3.3 \times 10^{15}$	
C	CIS	none	25	8	22	30	$8.9 \times 10^{15}$	-1
		RbF		30	70		$8.7 \times 10^{15}$	
	CIGS	none	25	7	7	36	$2.1 \times 10^{15}$	-19
		RbF		25	28		$1.0 \times 10^{15}$	
	ACIS	none	-22	13	13	44	$6.7 \times 10^{14}$	-7
		KF		64	71		$5.2 \times 10^{14}$	

$\tau_{bulk}$  values extracted using this approach are listed in Table 2. Significant increases after PDT were observed for all devices. Increased minority carrier lifetime is primarily attributed to reduced non-radiative recombination because  $\tau_{bulk} = 7-224$  ns is well below the radiative lifetime,  $\tau_R \sim 1000$  ns ( $\tau_R = 1/(BN_A)$  where  $B = 1.67 \times 10^{10}$  cm<sup>3</sup>s<sup>-1</sup><sup>[34]</sup> and  $N_A$  values are listed in Table 2 and discussed below). The  $\tau_{bulk}$ -associated voltage increase can be estimated by<sup>[35]</sup>

$$\Delta V_{OC,bulk} = \frac{kT}{q} \ln \left( \frac{\tau_{bulk,PDT}}{\tau_{bulk,untreated}} \right). \quad (7)$$

Voltage improvements  $\Delta V_{OC,bulk}$  due to increased bulk lifetime after PDT ranged from 30 to 71 mV, listed in Table 2. Given that recombination center concentration ( $N_T$ ) is linear with the recombination rate,  $\tau_{bulk} = \sigma v_{th} N_T$ , where  $\sigma$  is capture cross section and  $v_{th}$  is thermal velocity, which has been observed in similar samples,<sup>[21, 22]</sup> the improvements to  $\tau_{bulk}$  in these devices likely originate from a reduction in mid-gap defect concentration.



**Figure 3.** TRPL decays for devices A (a), B (b), and C (c). Gray lines show the region of fit. C-V profiles for devices A (d), B (e), and C (f). Symbols indicate the 0 V point from which  $N_A$  was extracted. Bar graphs in (g) indicate voltage changes after PDT due to bulk lifetime  $\Delta V_{OC,bulk}$  (light blue) and absorber doping  $\Delta V_{OC,NA}$  (middle blue, dotted). The combined  $\Delta V_{OC,bulk} + \Delta V_{OC,NA}$  (royal blue, lines) is compared with the  $V_{OC}$  voltage change due to PDT  $\Delta(V_{OC,sq} - V_{OC})$  (dark blue, solid) (compare to Figure 2(b)).

Next, we consider doping changes after PDT and their effect on voltage. Voltage changes  $\Delta V_{OC,NA}$  due to change in  $N_A$  can be similarly quantified by application of Equation (7), with  $N_{A,PDT}$  in the numerator and  $N_{A,untreated}$  in the denominator. Figure 3(d-f) shows the carrier concentration profiles for each device, and Table 2 provides  $N_A$  values from the zero-voltage point and the voltage changes  $\Delta V_{OC,NA}$  associated with PDTs.

Unlike voltage improvements from increased  $\tau_{bulk}$ ,  $N_A$  values generally decreased after PDT and induced voltage loss. This agrees with variable changes in  $N_A$  after PDT reported in the literature.<sup>[12, 13, 36-39]</sup> However, absolute  $\Delta V_{OC,NA}$  values were smaller than  $\Delta V_{OC,bulk}$  such that a net positive voltage change due to these two mechanisms is expected in PDT devices.

Voltage changes  $\Delta V_{OC,bulk}$ ,  $\Delta V_{OC,NA}$ , their combination ( $\Delta V_{OC,bulk} + \Delta V_{OC,NA}$ ), and the  $V_{OC}$  voltage change loss after PDT,  $\Delta(V_{OC,SQ}-V_{OC})$ , are given in Figure 3(g). Comparison between the latter two categories reveals whether bulk lifetime and carrier density constitute the dominant mechanisms for voltage change after PDT. For almost all devices the anticipated voltage improvement via  $\tau_{bulk}+N_A$  was larger than was actually achieved  $\Delta(V_{OC,SQ}-V_{OC})$ .

CIS and CIGS devices A and C demonstrated that the voltage change after RbF PDT was dictated primarily by  $\tau_{bulk}$  and  $N_A$ : only 12, 4, and 8 mV respectively were not accounted for with these two mechanisms. The remaining difference could be attributed to interface recombination, including back contact/band bending.

Alternatively,  $\tau_{bulk}$  and  $N_A$  were not the only significant mechanisms of voltage change in the other devices. A range of voltage discrepancies from 38 to 59 mV remained between total voltage loss and  $\tau_{bulk}+N_A$ . This indicates that mechanisms which were not included in these voltage change calculations such as interface recombination and/or back contact/band bending, were somewhat substantial in these devices. Early-time TRPL fits ( $\tau_I$ ) and front interface recombination velocity ( $S_{front}$ ) calculations, provided in the Supporting Information section, showed an increase in  $S_{front}$  for devices B after PDT. This increase suggests that front interface recombination likely contributed non-negligibly to voltage loss in these devices, although a method for voltage loss quantification of front and back interface contributions is not presently known.

Additional separation of front and back interface recombination in any of the devices would require simulations<sup>[22, 40]</sup> and temperature-dependent J-V measurements. These techniques extended beyond the scope of this work but could be enacted in future work to extract interface recombination parameters and differentiate between front and back interface contributions. Wolter et al.<sup>[24]</sup> demonstrated that sub-band states can also contribute to non-

radiative voltage losses, which may be an additional mechanism that impacts the  $\Delta V_{OC,bulk} + \Delta V_{OC,NA}$  and  $V_{OC,SQ} - V_{OC}$  voltage discrepancy.

Figure 3 highlights that independent of fabrication process or structure, PDTs increase  $\tau_{bulk}$ . Net acceptor concentration, however, generally decreased in devices with PDT. Therefore, one route to increased voltage is through improved understanding and control of acceptor concentration in PDT devices. A representation such as Figure 3 conveys only relative voltage changes between devices; therefore, it is important to utilize this representation in conjunction with Figure 2. Together, these depictions outline a more well-defined path to targeted voltage increases by providing information about primary and secondary voltage loss categories in devices and sub-mechanisms which generate voltage improvements.

### 3. Conclusion

Voltage loss identification and reduction is important for increased solar cell power conversion efficiency. For CIGS PV, this includes material improvements (e.g., trap density reduction through PDT processes) and device design advancement (such as absorber GGI grading). To better understand mechanisms that cause voltage losses, we applied consistent characterization methods to CIGS-based solar cells manufactured at three institutions with variation in fabrication, bandgap, absorber structure, PDT, and efficiency.

Two voltage loss categories, radiative and non-radiative (SRH), were delineated through EQE measurements. These categories were further described by parameters which correspond to physical mechanisms: non-ideal, sub-band state absorption, bulk lifetime, and net acceptor concentration.

Total voltage loss ( $V_{OC}$  relative to the bandgap-dictated Shockley-Queisser voltage) summed to over 180 mV in each CIGS device, with SRH the dominant loss mechanism. SRH contributed >75% compared to <25% from radiative voltage loss regardless of fabrication method, device architecture, or PDT. Generally, PDTs decreased the total voltage loss, driven primarily by SRH loss reduction, and assisted in some cases by reduced radiative losses.

Bulk lifetime was the most significant predictor of SRH voltage changes after PDT. Determined by fits to voltage biased TRPL data,  $\tau_{bulk}$  increased after PDT with up to 75 mV of predicted voltage improvement. There was variation in the effect of acceptor carrier concentration on voltage in untreated and PDT samples; most devices demonstrated smaller  $N_A$  and voltage reduction after PDT. This highlights a path to further voltage improvements via maintenance or increases in  $N_A$  with PDT. The role of interface recombination appeared to vary between devices; future work could include TRPL simulations and temperature-

dependent J-V measurements to separate front and back interface mechanisms. Thus, this work demonstrates that a multi-pronged approach to PV voltage loss analysis is necessary to understand voltage loss mechanisms and pathways to improvement.

#### 4. Methods

##### Device Fabrication

Devices were provided by three institutions, labeled “A”, “B”, and “C”. Each device is described by their PDT: untreated (no PDT) and RbF from institution A; untreated (no PDT), RbF+S, and RbF+In+S from institution B; and CuInSe<sub>2</sub> (CIS), CIS RbF, CIGS, CIGS RbF, (Ag,Cu)InSe<sub>2</sub> (ACIS), and ACIS KF from institution C.

##### *A Devices: Fabrication*

A devices had a Mo-coated soda-lime glass/CIGS/CdS/i-ZnO/ZnO:Al structure described fully in.<sup>[41]</sup> The 2.0-2.5 μm CIGS absorber was deposited by co-evaporation in a five-unit evaporation vacuum system. The first stage consisted of In, Ga, and Se depositions, and the second stage included Cu and Se deposition for a Cu-rich intermediate phase followed by In, Ga, and Se until a final Cu-poor composition was achieved. This created a linear grading profile.<sup>[41]</sup> Substrate heater temperatures of ~450 °C and ~650 °C were used for units one and two, respectively. The subsequent two units were used for sample cool down and the fifth unit was used for the PDT. The PDT process included a ramp up of the RbF source temperature for RbF evaporation onto the CIGS.

A 50 nm CdS buffer layer was deposited on the absorber by chemical bath deposition (CBD) followed by an RF-sputtered 80-nm undoped ZnO layer and DC-sputtered 400-nm Al-doped ZnO window layer. Finished device areas were ~2 mm<sup>2</sup>.

##### *B Devices: Fabrication*

B devices had a soda-lime glass/Mo/CIGS/CdS/ZnO/ZnO:Al/metallic grid structure. Complete fabrication details are provided by Polyxeni et al.<sup>[42]</sup> The polycrystalline CIGS absorber was deposited by a three-stage co-evaporation process to achieve a notch graded bandgap. The first stage consisted of In and Ga co-evaporation in a Se atmosphere at a substrate temperature of 375 °C. In stage two, Cu was evaporated in a Se atmosphere until the film became Cu-rich. The third stage consisted of In and Ga co-evaporation in a Se atmosphere until the film turned Cu-poor. Stages two and three were performed at a substrate temperature of 575 °C. PDT was enacted in a separate co-evaporation vacuum system with a substrate temperature of 350 °C. The RbF+S device received 15 nm of RbF evaporated (3 nm/min) in S excess (120 nm/min). The RbF+In+S was treated simultaneously with 15 nm of RbF (3 nm/min) and 20 nm of In (4 nm/min) in S excess.

A rinse in aqueous ammonia solution ( $1 \text{ molL}^{-1}$ ) was used to remove fluoride phases from the surface. CdS was deposited on all devices by CBD using 22-ml ammonia ( $1 \text{ molL}^{-1}$ ), 6-ml thiourea ( $9.5 \times 10^{-2} \text{ molL}^{-1}$ ), and 6-ml cadmium acetate dihydrate ( $2.6 \times 10^{-3} \text{ molL}^{-1}$ ). The CBD process was 360 s for the PDT devices and 420 s for the untreated device. The ZnO/ZnO:Al bilayer was RF-sputtered and electron beam evaporation was used to deposit the metallic grids through a shadow mask for device areas of  $0.5 \text{ cm}^2$ .

### *C Devices: Fabrication*

C devices had a soda-lime glass/Mo/Cl(Ga,Ag)Se/CdS/i-ZnO/ITO/metallic grid structure (see<sup>[43, 44]</sup> for full process details). The  $\sim 2 \text{ }\mu\text{m}$  CIS absorber and its Ga and Ag alloys were fabricated in a three-stage co-evaporation system. In and Ga (when used) were deposited in the first stage, Cu and Ag (when used) during the second stage, and In and Ga (when used) again during the third stage. A constant Se flux was employed throughout the evaporation with an overpressure maintained at a molar flux rate of greater than six times the total of all metals. Substrate temperatures were  $350 \text{ }^\circ\text{C}$  for the first stage, and  $580 \text{ }^\circ\text{C}$  for both the second and third stages. For PDT samples substrates were cooled to  $350 \text{ }^\circ\text{C}$  in the same system while the alkali-fluoride source ramped to evaporation temperature. The samples were exposed to alkali-fluoride flux for 7.5 min. The Se flux used during absorber growth was kept constant during PDT.

A 50 nm CdS layer was deposited by CBD after the CIS-based absorber, followed by a RF sputter-deposited 50 nm i-ZnO layer. Finally, a 150 nm ITO layer was deposited, and Ni-Al grids were subsequently deposited by electron beam deposition. Devices were delineated by mechanical scribing for cell areas of  $1.0 \text{ cm}^2$ .

### **Device Characterization**

Current density-voltage (J-V) data were measured at standard test conditions: simulated 1-sun AM 1.5G illumination, room temperature, and four-point probe contacting such that  $V_{OC}$ , short-circuit current density ( $J_{SC}$ ), fill factor ( $FF$ ), and efficiency ( $\eta$ ) were extracted. A devices were measured with a WACOM Class A (IEC-60904-9) solar simulator, B devices were measured with an Oriel Xenon lamp with AM1.5 filter and device temperatures maintained at  $25 \text{ }^\circ\text{C}$  by Peltier controls, and C devices were also measured with an Oriel lamp. External quantum efficiency ( $EQE$ ) spectra were measured between 300-1400 nm on an Oriel 200 system with no external illumination or voltage bias applied. Acceptor carrier concentrations were determined using Mott-Schottky analysis of capacitance-voltage (C-V) data.<sup>[45]</sup> The C-V profiles of devices A and C were measured at room temperature using a Boonton 7200 capacitance meter with a measurement frequency of 1 MHz and voltage biases

from -1 to 0 V. C-V profiles of B devices were measured at room temperature using an Agilent 4294A precision impedance analyzer with a measurement frequency of 40 kHz across a voltage range of -1.0 to +0.5 V. Despite the different measurement frequencies, each capacitance measurement had a Q-factor  $> 5$ , indicating accurate capacitance measurements across all devices.<sup>[45]</sup>

Time-resolved photoluminescence (TRPL) was measured with excitation wavelength of 640 nm and fluence  $1.3 \times 10^{12} - 1.0 \times 10^{14}$  photons  $\text{cm}^{-2}$  pulse<sup>-1</sup> (60  $\mu\text{m}$  laser beam diameter). TRPL decays were first measured at various injection levels to identify injection-independent ranges (low injection), which were implemented for final measurement and analysis. 0.3-ps pulses and 1.1 MHz repetition rate were used. Time-correlated single photon counting was used for data collection. A voltage bias of -0.5 – +1.0 V was applied across the device contacts for voltage-biased TRPL measurements. Single exponential fits of the TRPL tail decays were performed with  $t > 3$  ns and are provided in the applicable figures.

### Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

### Acknowledgements

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technology Office (SETO) Award Number DE-EE0008755.

The authors acknowledge German Federal Ministry for Economic Affairs and Energy under Project Number 03EE1078 (ODINCIGS).

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Received: ((will be filled in by the editorial staff))

Revised: ((will be filled in by the editorial staff))

Published online: ((will be filled in by the editorial staff))

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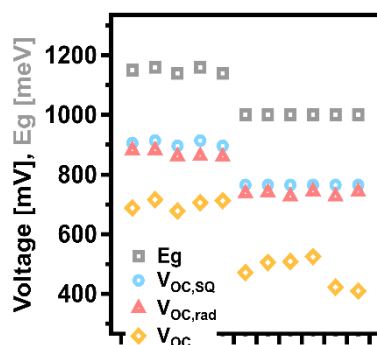
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This work presents an electro-optical voltage loss quantification methodology for photovoltaic devices. Voltage losses in the CIGS devices analyzed were dominated by non-radiative recombination (greater than 75% loss contribution) regardless of differences in device bandgap, absorber structure, post deposition treatment, and efficiency. Post deposition treatments decreased voltage loss through reduced non-radiative recombination, specifically by increased minority carrier lifetime.

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### Non-Radiative Recombination Dominates Voltage Losses in Cu(In,Ga)Se<sub>2</sub> Solar Cells Fabricated Using Different Methods



## Supporting Information

**Non-Radiative Recombination Dominates Voltage Losses in Cu(In,Ga)Se<sub>2</sub> Solar Cells Fabricated Using Different Methods**

*Alexandra M. Bothwell\*, Jake Wands, Michael F. Miller, Ana Kanevce, Stefan Paetel, Polyxeni Tsoulka, Thomas Lepetit, Nicolas Barreau, Nicholas Valdes, William Shafarman, Angus Rockett, Aaron R. Arehart, and Darius Kuciauskas*

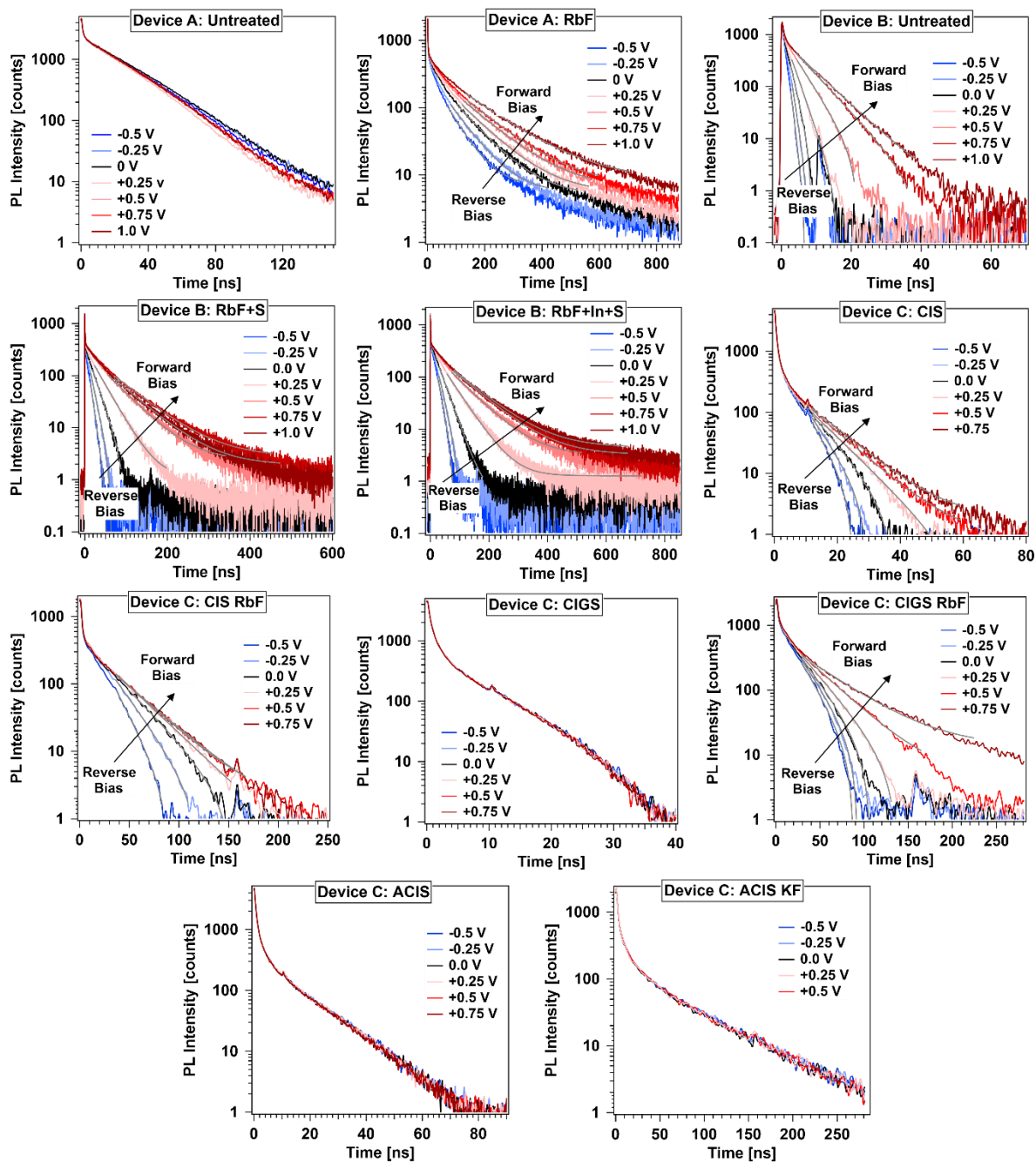
**Figure S1** provides the voltage biased TRPL decays for all devices. Bias voltage ranged from -0.5 V to +0.75 V or +1.0 V, where the maximum forward bias was at least 250 mV greater than device  $V_{OC}$ . As discussed in the primary text, some devices demonstrated voltage-bias dependence (which can be due to changes in interface recombination and electron extraction into the TCO) while others did not due to field effects, low doping, or non-standard transport mechanisms like trapping and detrapping.<sup>[32, 33]</sup>

Effective lifetimes,  $\tau_{eff}$ , were determined by a single exponential fit to the tail of the biased TRPL decays (fit regions are provided in Figure S1). **Figure S2** shows  $\tau_{eff}^{-1}$  vs. applied voltage for all devices where voltage-dependence was observed. 3-order polynomial fits according to Equation (6) are shown by solid and dashed lines for untreated and PDT devices, respectively, deriving  $\tau_{bulk}$  (Table 2).

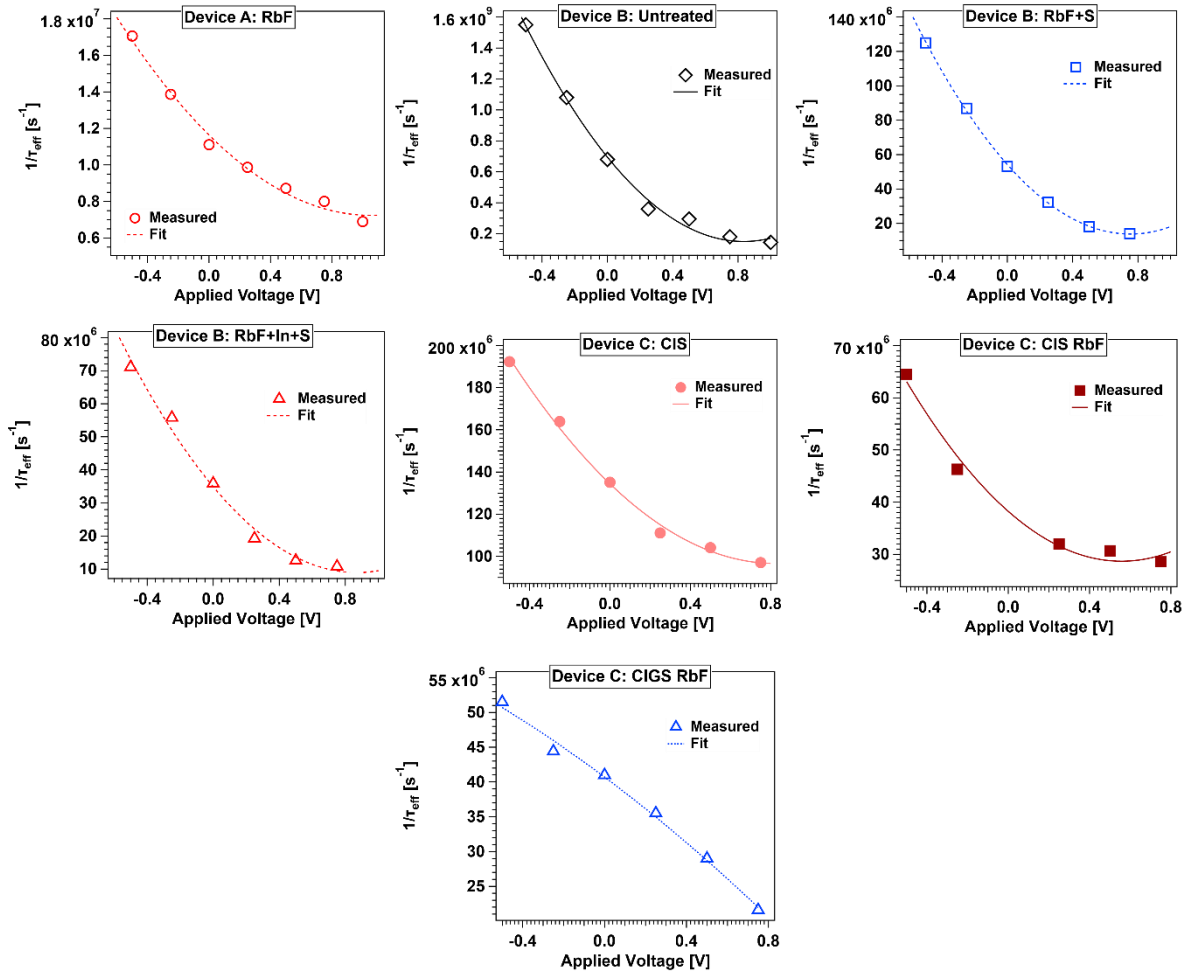
**Figure S3** shows early-time TRPL decays for all devices and Table S1 lists initial decay lifetimes ( $\tau_1$ ) and corresponding  $S_{front}$  values. Because all of the samples have fairly long bulk lifetimes, the surface component of the initial lifetime is considered to be much shorter than the bulk lifetime such that  $S_{front}$  is determined by:<sup>[46]</sup>

$$S_{front} = \frac{1}{\alpha\tau_1} \quad (S1)$$

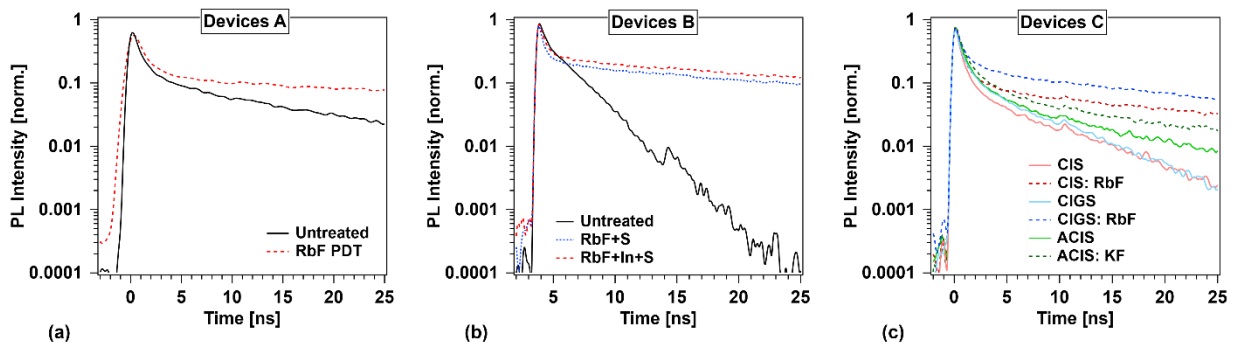
where  $\alpha$  is the absorption coefficient taken to be  $5 \times 10^4 \text{ cm}^{-1}$  at the 640-nm TRPL excitation wavelength. No significant differences in  $S_{front}$  before and after PDT were observed except for B devices. These devices demonstrated a notable increase in  $S_{front}$  after both RbF+S and RbF+S+In PDTs which may in part explain the large discrepancy between device voltage improvements ( $V_{OC,SQ} - V_{OC}$ ) and predicted improvements due to  $N_A + \tau_{bulk}$  (Table 2). For these devices, front surface recombination appears to contribute non-negligibly to voltage loss.



**Figure S1.** TRPL decays measured with electrical bias (indicated in the legends) applied to the solar cells. Gray lines show the region of fit. Most devices demonstrated expected voltage dependence while some were voltage-independent due to field effects, trapping, or doping level.



**Figure S2.** Rate (inverse effective lifetime) vs. applied voltage for TRPL data in Figure S1. Lines show 3-order polynomial fits to Equation (6) and are used to determine bulk lifetime.



**Figure S3.** Initial part of TRPL decays used to estimate front interface recombination velocities  $S_{front}$  (Table S1)

Table S1. Initial Lifetimes and Resultant  $S_{front}$

Device	Absorber	PDT	$\tau_1$ [ns]	$S_{front}$ [ $\text{cm s}^{-1}$ ]
A	CIGS	none	1.1	$1.8 \times 10^4$
		RbF	1.9	$1.1 \times 10^4$
B	CIGS	none	1.35	$1.5 \times 10^4$
		RbF+S	0.49	$4.1 \times 10^4$
		RbF+In+S	0.59	$3.4 \times 10^4$



C	CIS	none	0.62	$3.3 \times 10^4$
		RbF	0.65	$3.1 \times 10^4$
	CIGS	none	0.69	$2.9 \times 10^4$
		RbF	0.81	$2.5 \times 10^4$
	ACIS	none	0.75	$2.7 \times 10^4$
		KF	0.86	$2.3 \times 10^4$