2.0 – 2.2 eV AlGaInP solar cells grown by MBE

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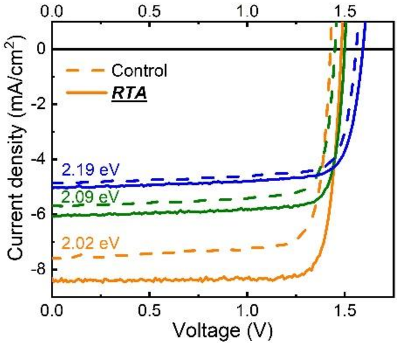
$(Al_xGa_{1-x})_{0.51}In_{0.49}P$ (AlGaInP), with a tunable bandgap energy (E_g) of 1.9 – 2.2 eV, is an ideal top cell material for high-efficiency multi-junction (MJ) solar cells with 5 – 6 junctions. However, AlGaInP growth is challenging by both molecular beam epitaxy (MBE) and metalorganic vapor phase epitaxy (MOVPE) due to O-related defects. Recent work has shown that the performance of MOVPE-grown AlGaInP solar cells can be greatly improved by growth at very high temperatures of ~740 – 780 °C [1]. However, the MBE growth temperature of AlGaInP is typically restricted to < 500 °C, making post-growth annealing a crucial step to improve material quality [2]. In this work, we report on MBE-grown 2.0 – 2.2 eV AlGaInP solar cells, as well as effects of rapid thermal annealing (RTA). All aspects of cell performance were improved by RTA, though the enhancement diminished at the highest E_g and Al content. A 14.3% efficiency (η) was achieved in an anti-reflection-coated (ARC) 2.0 eV AlGaInP solar cell, closely matching record cells grown by MOVPE.

Cells with E_g = 2.02, 2.09, and 2.19 eV were grown by solid-source MBE at substrate temperatures of ~480 °C and V/III ratios of 10 – 15, while RTA was conducted at ~700 – 800 °C prior to device fabrication.

RTA led to improvements in internal quantum efficiency (IQE) for all cells, though the gain was most pronounced in the 2.02 eV AlGaInP. Short-circuit current density (J_{SC}) was accordingly boosted, as shown in the figure and table. V_{OC} also increased, together with a dark current reduction of 3 – 4 ×. The boosts in J_{SC}, V_{OC}, and efficiency show that RTA substantially improves the minority carrier lifetime and diffusion length in AlGaInP. An efficiency of 14.3% was achieved in the 2.02 eV AlGaInP cell after RTA with ARC, closely matching the record set by MOVPE.



LIV of uncoated AlGaInP solar cells before and after ***RTA***

E_g (eV)	J_{sc} (mA/cm^2)	V_{oc} (V)	η (%)
2.19	4.87→***5.04***	1.56→***1.59***	5.9→***6.2***
2.09	5.67→***6.08***	1.45→***1.50***	6.5→***7.5***
2.02	7.64→***8.46***	1.43→***1.48***	8.7→***10.9***

[1] Perl, E. E., et al. *J. Photovolt.* 6.3 (2016): 770-776.
[2] Faucher, J., et al. *Appl. Phys. Lett.* 109.17 (2016): 172105.

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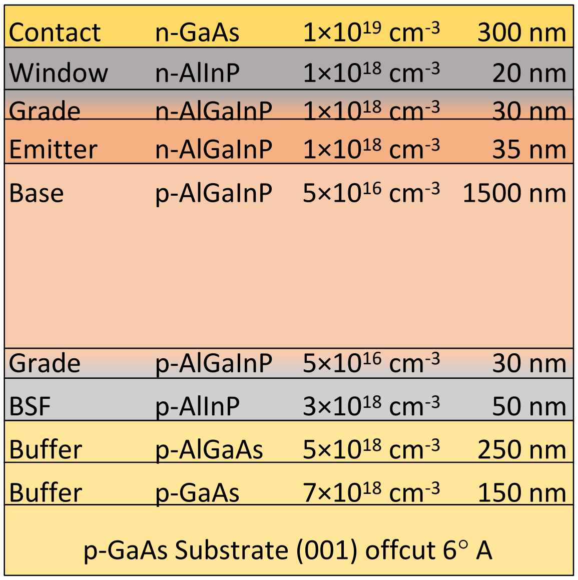


Layer	Material	Doping	Thickness
Contact	n-GaAs	1×10^{19} cm^{-3}	300 nm
Window	n-AlInP	1×10^{18} cm^{-3}	20 nm
Grade	n-AlGaInP	1×10^{18} cm^{-3}	30 nm
Emitter	n-AlGaInP	1×10^{18} cm^{-3}	35 nm
Base	p-AlGaInP	5×10^{16} cm^{-3}	1500 nm
Grade	p-AlGaInP	5×10^{16} cm^{-3}	30 nm
BSF	p-AlInP	3×10^{18} cm^{-3}	50 nm
Buffer	p-AlGaAs	5×10^{18} cm^{-3}	250 nm
Buffer	p-GaAs	7×10^{18} cm^{-3}	150 nm
p-GaAs Substrate (001) offcut 6° A			

Fig. 1: Structure of 2.02, 2.09 and 2.19 eV AlGaInP solar cells investigated in this work.

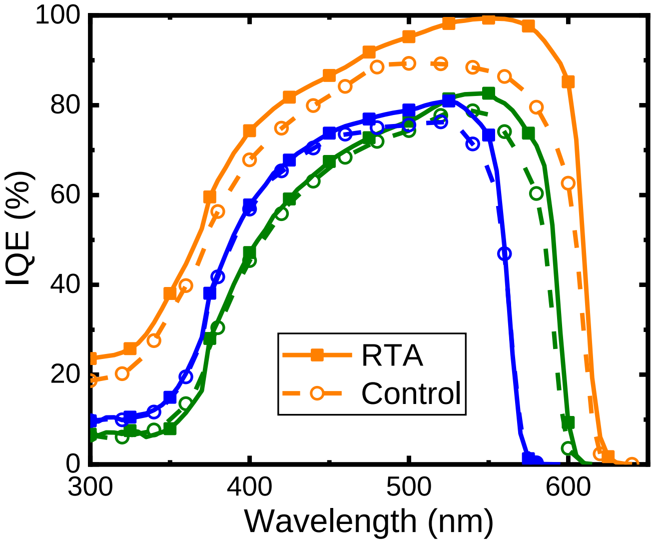


Fig. 2: IQE before (○) and after (▪) RTA. While all cells were improved by RTA, the 2.02 eV cell (orange) gained most.

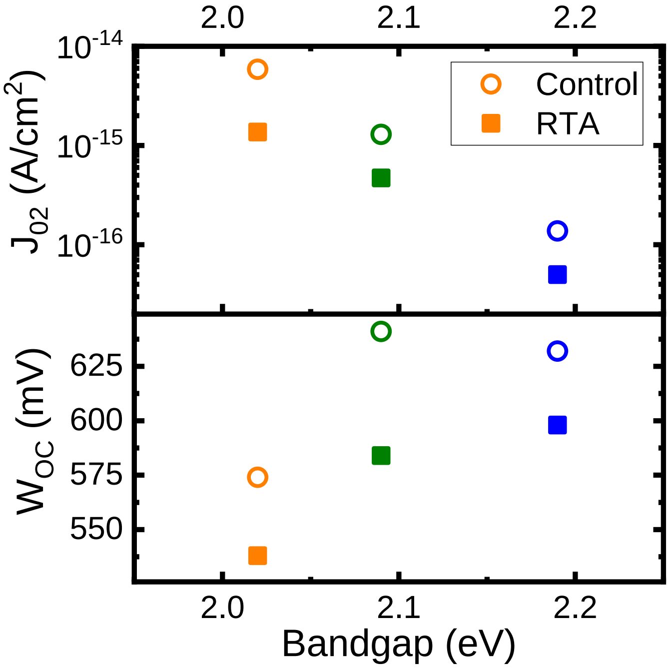


Fig. 3: Decrease of bandgap-voltage offset W_{OC} (=$E_g/q-V_{OC}$) and dark current J_{02} as a function of E_g, indicating improvement in minority carrier lifetime after RTA.

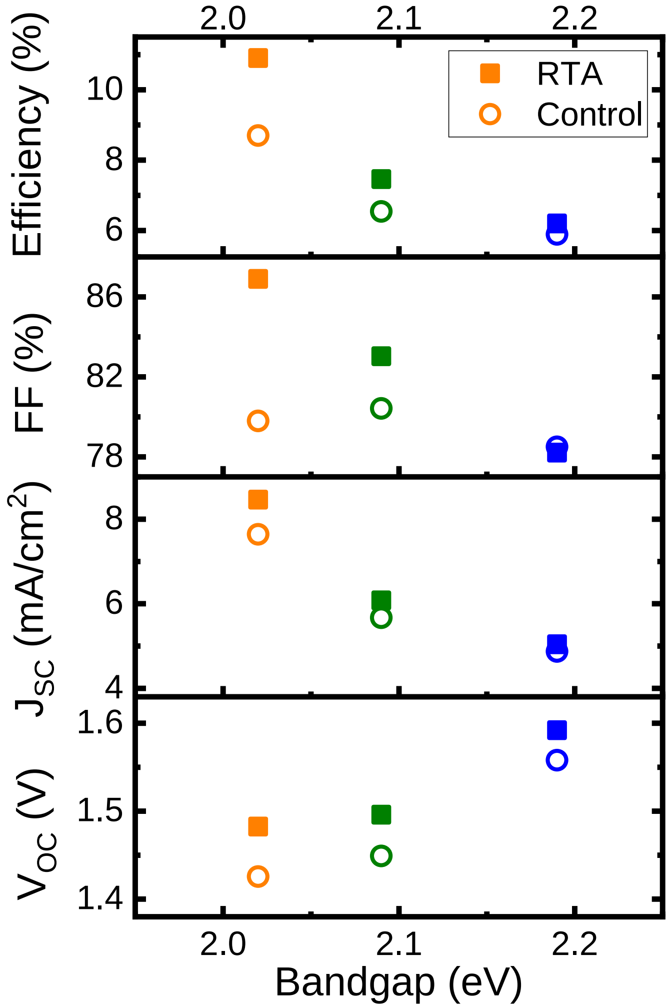
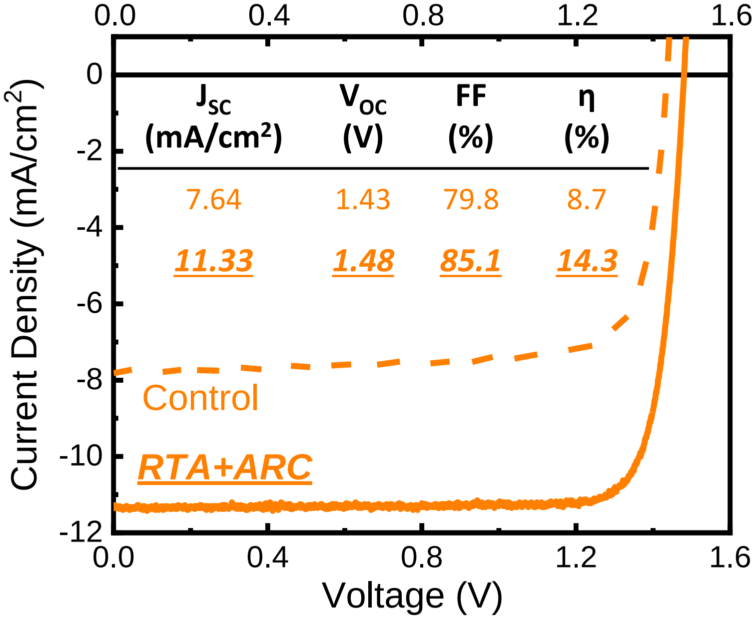


Fig. 4: All aspects of AlGaInP solar cell performance (J_{SC}, V_{OC}, FF and efficiency) improved by RTA, as a result of improved materials quality (no anti-reflection coating, ARC).



J_{SC} (mA/cm²)	V_{OC} (V)	FF (%)	η (%)
7.64	1.43	79.8	8.7
11.33	***1.48***	***85.1***	***14.3***

Fig. 5: 2.02 eV AlGaInP solar cell efficiency increased to 14.3% with RTA and double-layer ARC, closely matching record-efficiency 2.02 eV AlGaInP cells by MOVPE.