SolAero 2020: III-V Metamorphic Graded Buffers

Cooperative Research and Development Final Report

CRADA Number: CRD-19-16398

NREL Technical Contact: Ryan France

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated under Contract No. DE-AC36-08GO28308

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Technical Report
NREL/TP-5900-96773
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Cooperative Research and Development Final Report

Report Date: August 22, 2024

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the CRADA final report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: SolAero Technologies Corp.

CRADA Number: CRD-19-16398

CRADA Title: SolAero 2020: III-V Metamorphic Graded Buffers

Responsible Technical Contact at NREL:

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Sponsoring DOE Program Office(s):

Office of Energy Efficiency and Renewable Energy (EERE), Solar Energy Technologies Office

Joint Work Statement Funding Table showing DOE commitment: No shared resources

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$.00
Year 2, Modification #1	$.00
Year 3, Modification #2	$.00
Year 4, Modification #3	$.00
TOTALS	$.00

Executive Summary of CRADA Work:

The effort by the National Renewable Energy Laboratory (NREL) for SolAero Technologies Corp (SolAero) will involve helping with four tasks: 1) Supporting the development, characterization, and optimization of metamorphic grades in III-V multi-junction solar cells, 2) Doping of III-V semiconductor materials and junctions, and 3) Incorporating strain balanced layers into solar cells, and 4) high efficiency germanium based solar cells.

CRADA benefit to DOE, Participant, and US Taxpayer:

- Enhances the laboratory's core competencies, and/or
- Uses the laboratory's core competencies, and/or
- Enhances U.S. competitiveness by utilizing DOE developed intellectual property and/or capabilities.

Summary of Research Results:

Task 1: Metamorphic Grades

In Task 1 NREL will support SolAero in the development, characterization, and optimization of metamorphic grades used in non-inverted III-V multi-junction solar cells.

Subtask 1.1: During Subtask 1.1 NREL will consult with SolAero in the design of experimental structures that will be grown by SolAero. NREL will be responsible for providing the technical expertise (e.g., Ryan France) to support SolAero. Based on experimental results, NREL will assist SolAero in the optimization of subsequent non-inverted structures grown by SolAero.

Subtask 1.2: NREL will assist in the characterization of the non-inverted structures grown by SolAero. This may include XRD characterization and analysis of material at NREL, as well as assisting in the interpretation of characterization done by SolAero.

Results

In collaboration with SolAero, NREL investigated the radiation hardness of metamorphic material as a function of Indium content in GaInAs solar cells. Each solar cell had a different metamorphic buffer resulting in a strain-matched GaInAs cell with variable composition. Woc and FF were analyzed before and after irradiation with 1e15 cm^{-2} 1 MeV electrons, shown in Fig. 1. EOL Woc was consistent for all alloys, with slightly less variation than BOL Woc.

In Figure 2, GaInAs cells with a variety of doping densities were grown and analyzed. Higher EOL Voc was achieved with higher doping density, potentially related to depletion width differences.

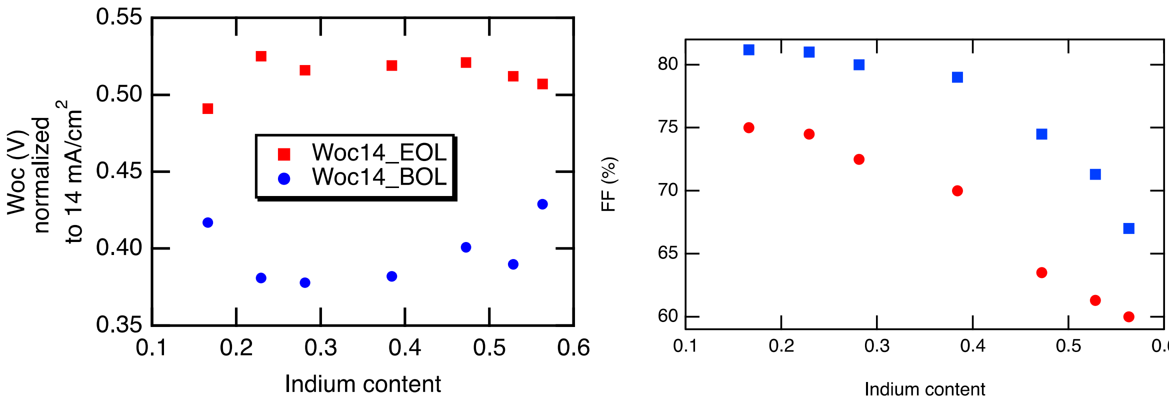

Fig. 1 (left) Woc (Eg-Voc) and (right) FF of GaInAs solar cells with variable composition, before (BOL) and after (EOL) electron radiation of 1 MeV electrons at 1e15 cm^{-2} fluence. The $Ga_{1-x}In_xAs$ composition varies from x=0.1 to 0.6, and so all cells are lattice mismatched to the underlying GaAs substrate, utilizing a metamorphic GaInP buffer. BOL and EOL Wocs are fairly consistent vs Indium content, while FF becomes lower and with increasing In content.

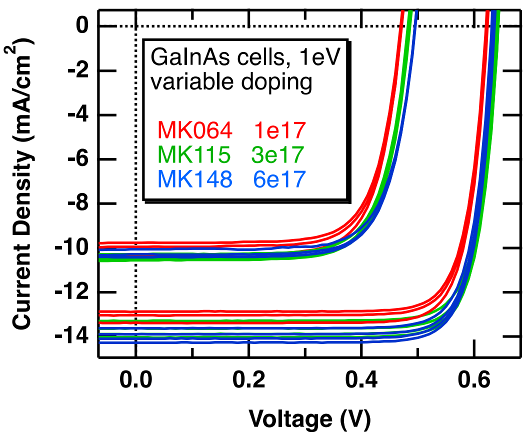

Fig. 2. IV curves of 1eV GaInAs cells before and after irradiation. The solar cells have variable carrier concentration. After irradiation, cells with lower doping, and thus larger depletion regions, have lower Voc.

NREL analyzed TRPL from AlGaInP double heterostructures provided by SolAero. Results are shown in Figure 3.

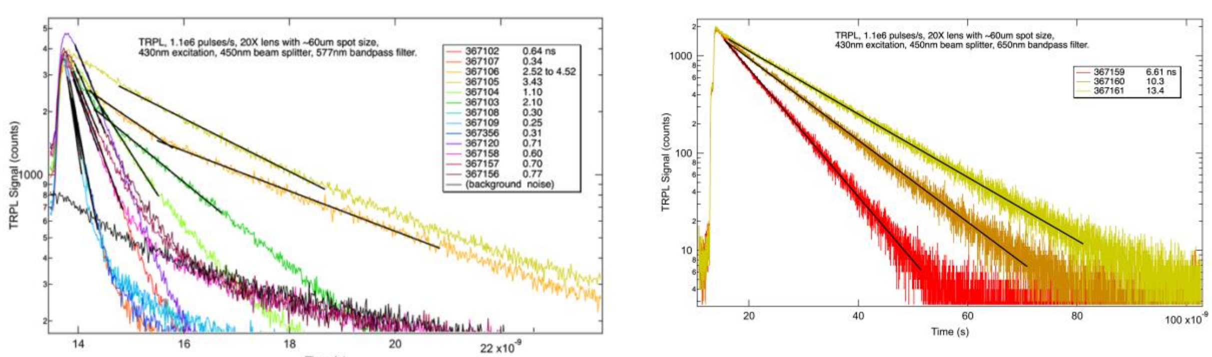

Fig. 3. TRPL of a variety of AlGaInP double heterostructures, provided by SolAero. Trends in data were interpreted by SolAero.

Task 2: Nitrogen Doping

In Task 2 NREL will demonstrate nitrogen doping of GaAs semiconductor material and junctions.

Subtask 2.1: NREL will grow GaAs material and demonstrate nitrogen doping and control.

Characterization will be by SIMS.

Subtask 2.2: NREL will grow single junctions of GaAs with 3 levels of nitrogen doping in the base region, as well as a control with no nitrogen doping, consulting with SolAero in the cell design. The cells (nominally 0.25 cm2 in area, at least 6 of each type for each N composition) will be processed using NREL's standard flow and provided to SolAero.

Results

Baseline front-junction GaAs devices were created with and without graded doping in the base, then analyzed before and after electron irradiation. Graded doping resulted in lower Voc but much higher Jsc and thus higher efficiency, shown in Fig. 4.

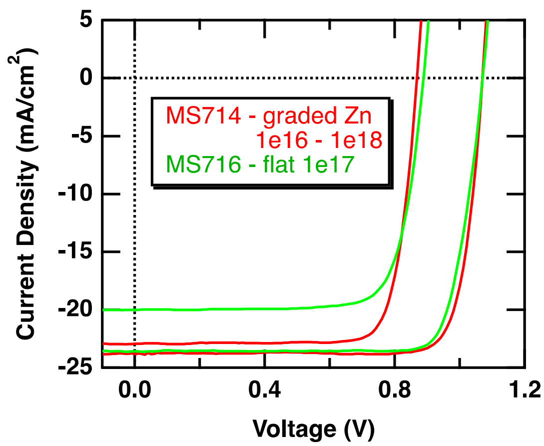

Fig. 4: JV curves of GaAs cells doped with constant doping or graded doping, before and after irradiation. Graded doping maintains a higher Jsc after irradiation, as expected.

Using graded doped cells, dilute nitrogen was slowly introduced into the cells, which resulted in a reduced bandgap and reduced voltage cells, shown in Fig. 5.

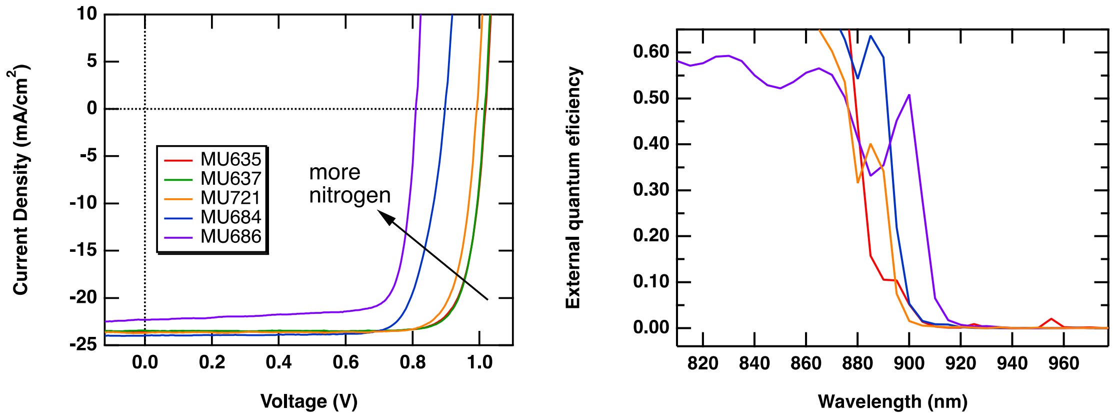

Fig. 5: JV curves and EQE of solar cells with increasing nitrogen content. Nitrogen is expected to reduce Voc but also increase the absorption range.

The devices with increasing nitrogen content had an increasing carrier concentration, as measured by CV, shown in Fig. 6. Devices were provided to SolAero for radiation testing.

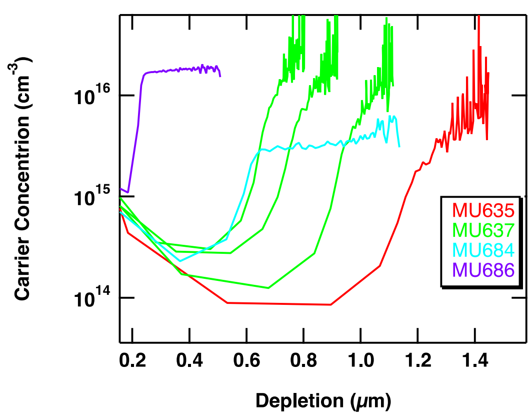

Fig. 6: Measured carrier concentration in the base of solar cells with increasing dilute nitrogen.

Task 3: InGaAs/GaAsN Strain Balanced Layers

In Task 3 NREL will incorporate strain balanced InGaAs/GaAsN layers into GaAs single junction cells.

Subtask 3.1: In collaboration with SolAero, NREL will grow single junction GaAs cell incorporating strain balanced InGaAs/GaAsN layers.

Subtask 3.2: NREL will process material from Subtask 3.1 into solar cells, nominally 0.25 cm2 in area, to be delivered to SolAero.

Results

This task was re-evaluated to utilize InGaAs/GaAsP MQWs instead of InGaAs/GaAsN MQWs. P-i-n devices were created with and without MQWs to isolate the impact of the MQWs degradation during irradiation. JV curves of cells with and without MQWs are shown in Fig 7, along with the QEs of the cells tested before and after irradiation and with voltage biasing. The voltage biasing shows how the collection efficiency of various portions of the cell was impacted. JVs show that the MQW cell loses more voltage and more current than the p-i-n cell without MQWs.

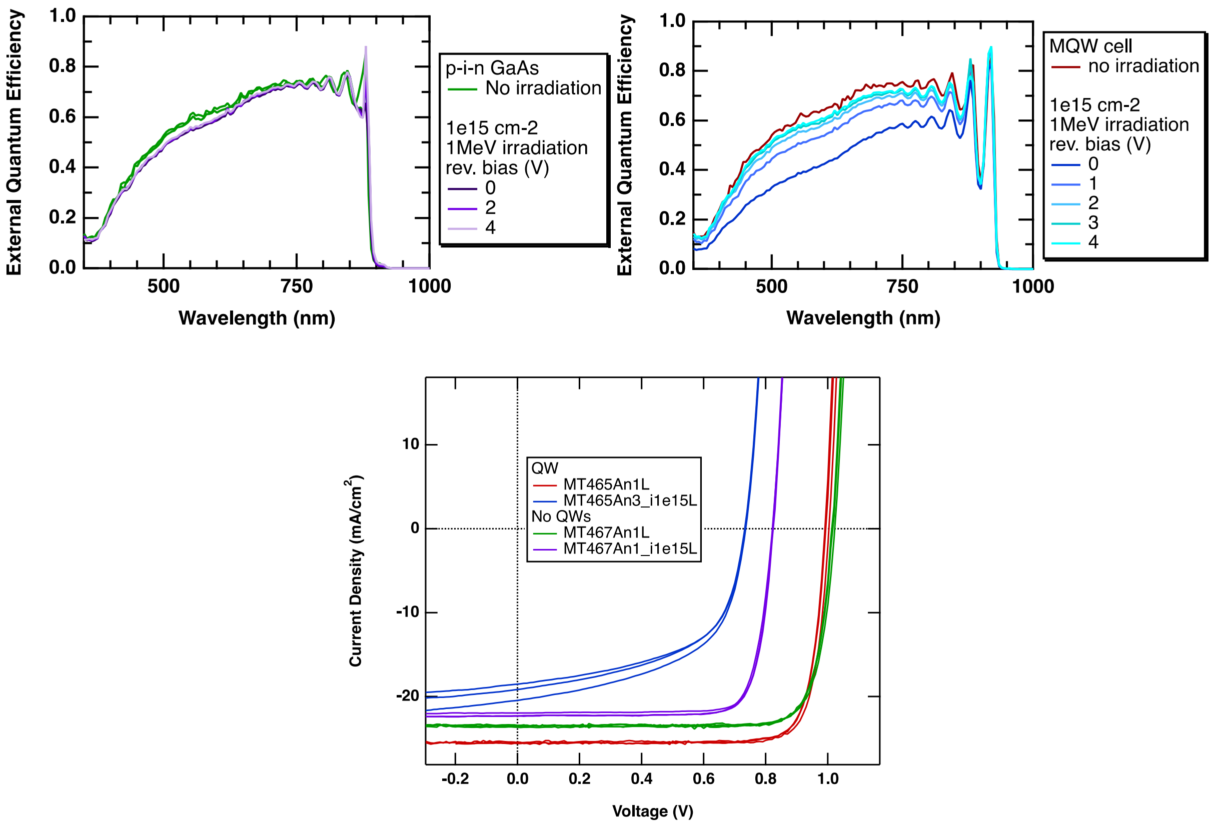

Fig. 7: (top) QE of p-i-n GaAs cells with (left) and without (right) MQWs, before and after irradiation and tested in variable voltage reverse bias conditions. (Bottom) JV curves of cells with and without MQWs before and after electron irradiation. BOL performance of QW cells has higher Jsc, but EOL performance suffers from large voltage and FF loss.

Task 4: Epitaxial Germanium

In Task 4 NREL will grow epitaxial Germanium solar cells.

Subtask 4.1, NREL will grow Ge isotype solar cells to demonstrate crystal quality and doping control.

Subtask 4.2, NREL will investigate III/V – Ge heterojunction solar cells, and will provide SolAero with any suitable devices.

Results

Epitaxial Ge cells were grown on Ge substrates, using a III-V passivating barrier on top of the epitaxial Ge. Spatial uniformity maps are shown in Fig 8. Some cells have high voltage, but the variability is high.

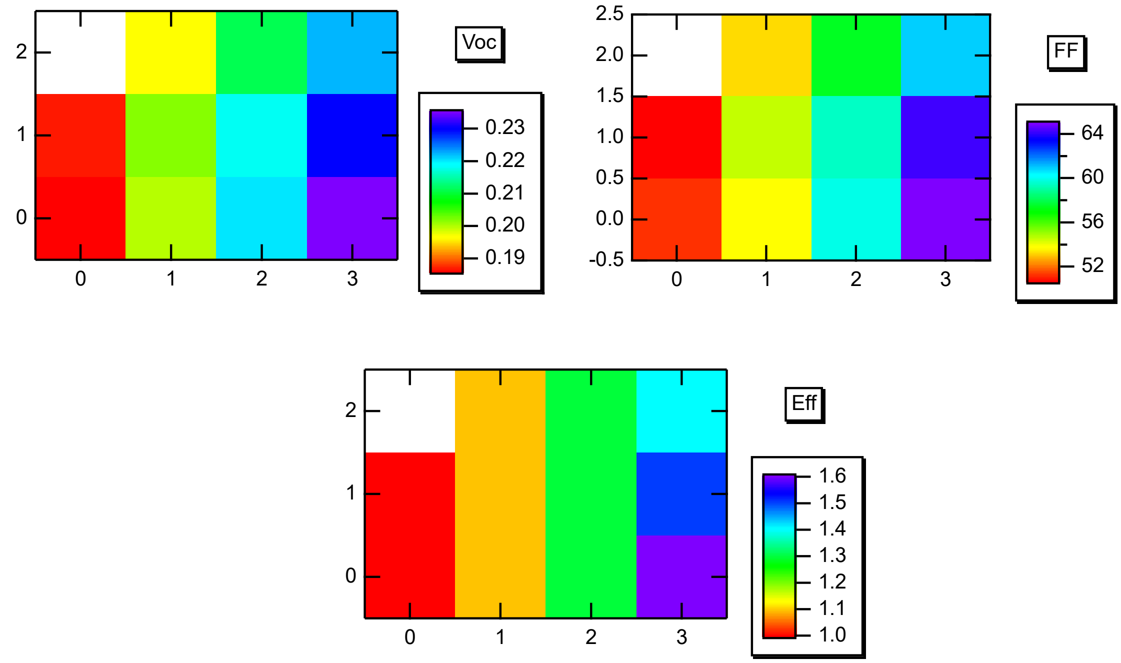

Fig. 8: Spatial uniformity map of Ge cells with epitaxial Ge emitters and III-V barriers. The X and Y axes represent cell numbers of a 3x4 grid. Each cell is 3mm x 3mm, separated by 1mm. Performance varies drastically across the wafer, with the best cells performing as good as high-quality standard diffused junction Ge cells.

Reporting and Final Deliverable

NREL shall participate, at a minimum, in monthly teleconferences with SolAero to discuss technical progress. Additional teleconferences are expected, and will be scheduled on an as needed basis. NREL will provide quarterly reports and a final report summarizing the outcomes, research progress, and results of the effort. NREL is also planning to write a CRADA final report for DOE showing the technical results and outcomes of the CRADA, allowing SolAero the opportunity for pre-submission review.

This report serves to meet the requirement for the CRADA Final Report with preparation and submission in accordance with the agreement's Article X.

References: None

Subject Inventions Listing: None

ROI#: None