State of the Art CdTe Cells

Cooperative Research and Development Final Report

CRADA Number: CRD-21-17858

NREL Technical Contact: Matthew Reese

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

Technical Report
NREL/TP-5K00-86709
June 2023

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Suggested Citation

Reese, Matthew. 2023. *State of the Art CdTe Cells: Cooperative Research and Development Final Report, CRADA Number CRD-21-17858.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-5K00-86709. https://www.nrel.gov/docs/fy23osti/86709.pdf.

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NOTICE

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 herein do not necessarily represent the views of the DOE or the U.S. Government.

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Cooperative Research and Development Final Report

Report Date: June 26, 2023

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: NanoSpray

CRADA Number: CRD-21-17858

CRADA Title: State of the Art CdTe Cells

Responsible Technical Contact at Alliance/National Renewable Energy Laboratory (NREL):

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Sponsoring DOE Program Office(s):

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

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1 Year 2, Modification #1	$75,000.00 $0.00
TOTALS	$75,000.00

Executive Summary of CRADA Work:

NREL and NanoSpray will cooperate to leverage NREL's existing solar cell processing facilities at NREL's Atmospheric Processing Platform to determine optimal processing method using 6" by 6" CdTe modules.

CRADA benefit to DOE, Participant, and US Taxpayer:

- Assists laboratory in achieving programmatic scope
- Uses the laboratory's core competencies

Summary of Research Results:

TASK EXPLANATIONS

BACKGROUND

This work is to be conducted in support of the American-Made Solar Prize. NanoSpray and NREL will work together to understand how novel technologies, such as those being developed by NanoSpray, can impact the development and economics of the Solar industry.

SCOPE OF WORK

NREL and NanoSpray will cooperate to leverage NREL's existing CdTe solar cell processing and characterization facilities as well as NREL's Atmospheric Processing Platform (APP) to determine optimal processing method for their novel contacts.

TASK #1 – Growth and Characterization of CdTe Thin Films

Subtask 1.1: Superstrate Cd (Se,Te) devices of varying thicknesses without back contacts shall be grown and doped at NREL on 3x3" coupons and shipped to NanoSpray for back contact preparation and growth. The Cd(Se,Te) absorber thickness shall be varied to facilitate the relative effect of back interface recombination on open-circuit voltage. The focus shall be to grow samples with a traditional Cu-defect chemistry, but a more limited number of samples shall be grown with an As-defect chemistry. Cu-doped samples shall be grown throughout the duration of the project, As-doped samples shall be grown later in the project.

Subtask 1.1 Result:

Best-known method NREL-grown Cd(Se)Te absorbers with a 500 nm CdSeTe (30% Se) layer were grown on Tec12d glass, then packaged and shipped to NanoSpray. 13% 900 nm thick absorbers (with gold contacts) were also grown at NREL and shipped to NanoSpray. The thinned devices, more sensitive to back interface effects due to the proximity of the main junction to the back surface, yielded a lower V_{OC} than their thick counterparts, particularly in the case of the thinned MXene. This was speculated to be due to an increased rate of recombination at the back surface from the NanoSpray ink materials due to unwanted intercalants from the MXene synthesis process (see Fig 1.2a).

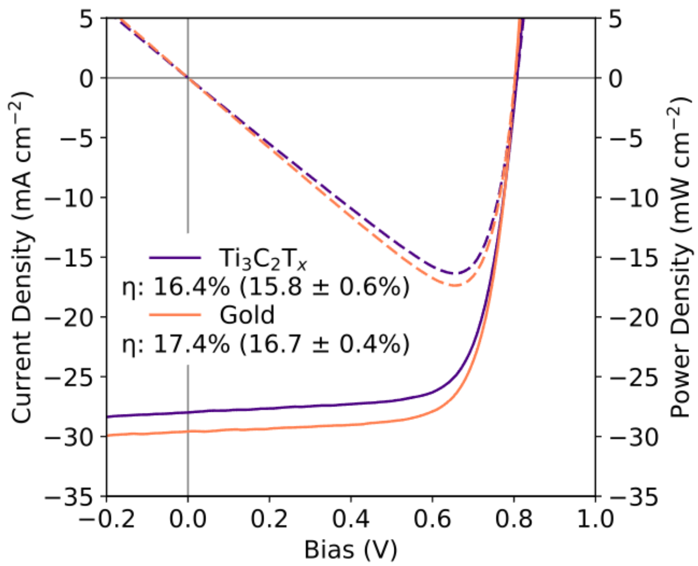

Figure 1.1.1. "Thick" absorber with Au and MXene contacts have current-voltage and power vs voltage representations that illustrate no loss in open-circuit voltage with the MXene and only a modest loss in current density due to the lack of reflectivity of the MXene relative to the Au.

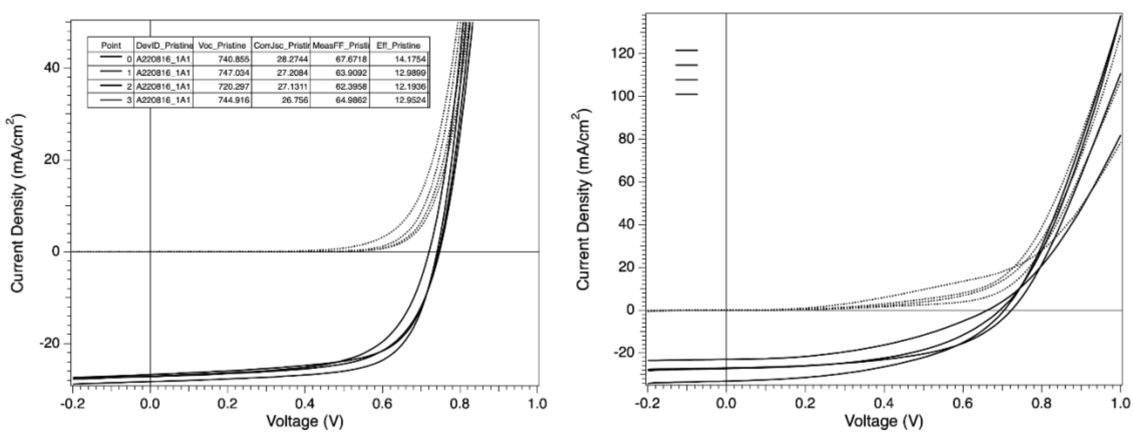

Figure 1.1.2. (a) Current density versus voltage curves for "thin" Cd(Se,Te) with an Au back contact. (b) Current density versus voltage curves for "thin" Cd(Se,Te) with a MXene back contact.

Subtask 1.2: Characterization using time-resolved photoluminescence (TRPL) and temperature dependent current voltage [JV(T)] on samples shipped from NanoSpray shall be performed at NREL. If alternative detailed characterization is deemed appropriate it shall be considered. TRPL measurements shall be performed in batches. JV(T) shall be performed on more limited sample sets.

Subtask 1.2 Result:

A publication came out of the work in this task which can be found at (https://doi.org/10.1002/solr.202200366). Time-resolved photoluminescence (TRPL) was used to probe the recombination associated with the back interface (MXene/CdTe) relative to different stages of device processing as illustrated in Figure 1a. Temperature dependent current voltage, JV(T), was used to assess the barriers associated with a baseline NREL back contact (gold) compared to a $Ti_3C_2T_x$ MXene contact.

The MXene contact was found to have a lower barrier (0.33 eV) compared to Au (0.46 eV). This greater than 0.1 eV improvement in barrier enabled a champion MXene cell with 16.4% efficiency, with an average efficiency of 15.8% across 16 cells. The reduced barrier height was confirmed with capacitance-voltage measurements.

The high work function of $Ti_3C_2T_x$ MXenes allows for low Schottky-barrier hole contacts to be made with CdTe surfaces. This has excellent implications for future CdTe devices, as a lower barrier height allows for the fabrication of CdTe devices with thinner active layers and raises the efficiency ceiling on CdTe devices as the carrier concentration and front interface recombination are improved. The promising results using $Ti_3C_2T_x$, the prototypical and most-studied MXene, suggest that the MXene family of materials may yield a rich vein of research for the formation of effective CdTe contacts. The use of other high work function MXenes may further lower the back contact barrier heights or even enable ohmic contacts with CdTe, further improving the V_{OC} and the FF.

The fast recombination associated with the MXene as seen by TRPL may be a place for further improvement moving forward, which may enable improvements in bifaciality.

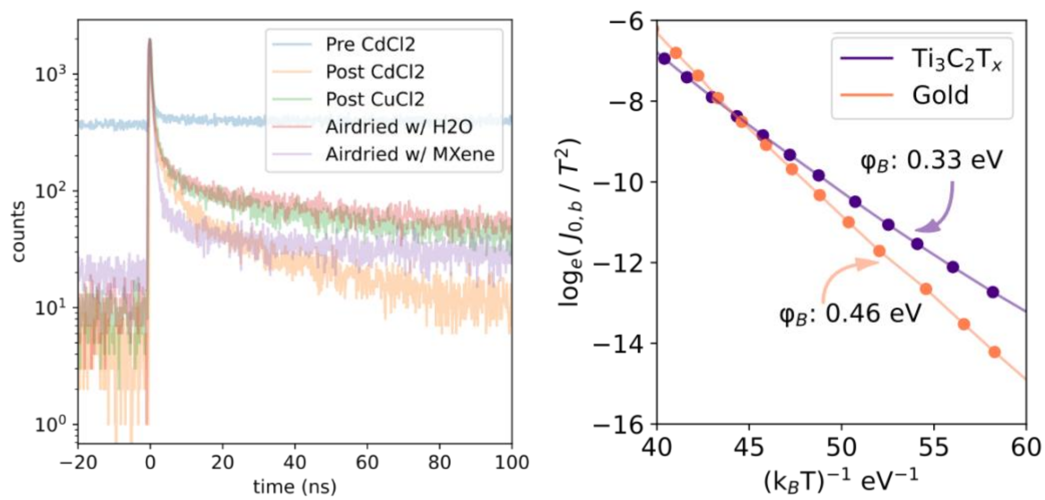

Figure 1.2 (a) TRPL decay curves of various samples at different stages in the fabrication process, with and without MXenes. (b) JV(T) of a sample with a reference gold contact compared to a MXene $Ti_3C_2T_x$ contact.

TASK #2 – Interconnect and Process Scaleup

Subtask 2.1: Ways to transition from a MXene contact to ribbons shall be explored at NREL and NanoSpray. Methods that will be considered include using electrically conductive adhesives directly to a MXene layer as well as to MXene layers that have been metallized. Both the initial contact resistance as well as stability of the structures upon thermal cycling shall be investigated.

Subtask 2.1 Result:

Electrically conductive adhesives were explored, but contact resistance and thermal cycling investigations were not pursued due to a reprioritization from NanoSpray.

Subtask 2.2: With consultation with Toledo Solar and NanoSpray, NREL shall demonstrate an encapsulation strategy for the 6x6" minimodules using an edge seal and encapsulant provided by Toledo Solar or with materials already available and know at NREL.

Subtask 2.2 Result:

The challenges in fabricating mini-modules precluded this work from taking place. Strategies on how to encapsulate modules were discussed with NanoSpray involving desiccated polyisobutylene (PIB) and a couple well-known encapsulants. Papers regarding the choice of edge seal selection and temperature requirements were shared with NanoSpray in the event that there is the desire to choose this in the future. These include:

DOI: 10.1002/pip.2374, DOI: 10.1002/pip.2465, https://doi.org/10.1038/s41560-018-0258-1

Subtask 2.3: NREL shall work on 6x6" CdTe minimodules provided by Toledo Solar with NanoSpray inks shipped to NREL. Ink formulations shall be modified by NanoSpray in consultation with NREL upon feedback of coating. NREL shall evaluate at least two of the following methods to deposit MXene layers: slot-die coating, blade-coating, and inkjet printing. NREL shall also work with its ESH group to facilitate laser scribing experiments to pattern MXene layers.

Subtask 2.3 Result:

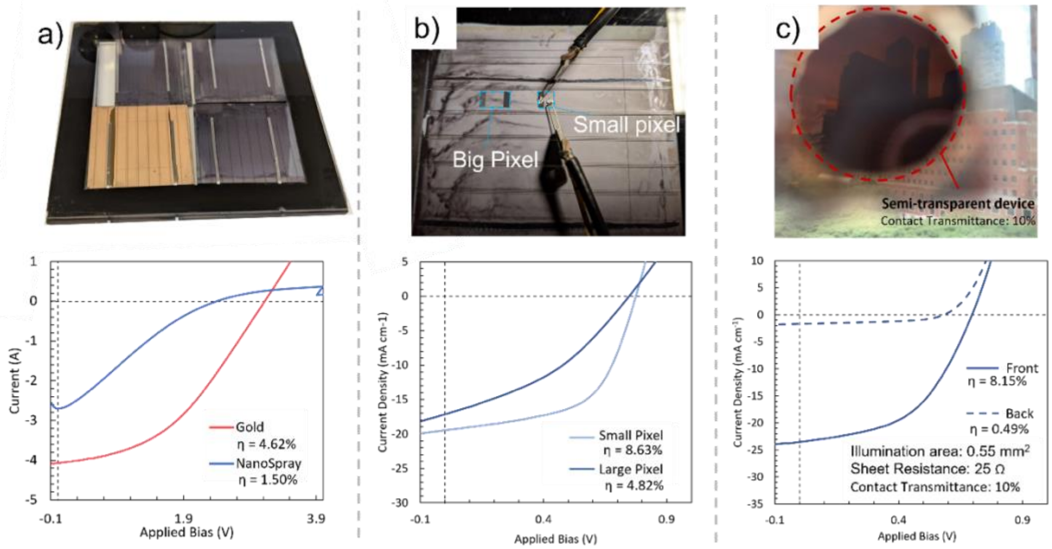

Figure 2.3 (a) JV curves for Gold- and NanoSpray MXene-contacted 4" x 4" mini-modules. (b) JV analysis of subcells within MXene-coated minimodule demonstrating series resistance and interconnection challenges. (c) Front-side and back-side semi-transparent CdTe device fabricated by blade-coating.

Mini-modules were fabricated on Toledo Solar absorbers which had been P1 scribed, backfilled with insulator, and P2 scribed at Toledo Solar's facilities. $Ti_3C_2T_x$ MXenes were shipped to NREL by NanoSpray and blade-coated onto CdTe substrates and then annealed at the temperatures specified by NanoSpray prior to co-locating a P3 scribe with the previous Toledo Solar scribes. The resulting minimodules were measured on a superstrate solar simulator at NREL, revealing significant "roll-under", characteristic of very high series resistance (Fig 2.3 a).

These series resistance losses may be attributed to either of two potential losses, either within the MXene material or within the interconnect between subcells. To investigate these losses, subcell pixels were scribed into the CdTe absorber on individual cells and JV characteristics investigated. A small pixel had a higher efficiency than the larger pixel indicating that the series resistance across the contact layer itself was contributing to these losses. However, the extent of the series resistances from this contact layer does not fully describe the losses in the mini-module, suggesting that there remain issues with interconnection through the Toledo Solar P2 scribes.

MXenes were blade-coated in both thick opaque layers and thin semitransparent layers. The process developed to fabricate thin MXene layers was used to fabricate an 8.15% semi-transparent device on a thinned CdTe absorber, with a 0.5% backside efficiency to demonstrate the potential use of MXenes as bifacial contacts.

Subject Inventions Listing:

None

ROI #:

None