A performance comparison between GaInP-on-Si and GaAs-on-Si 3-terminal tandem solar cells

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Highlights

New 3-terminal tandem superstrate design provides mechanical support to both subcells
Third terminal enables extraction of surplus photocurrent from mismatched subcells
Data show that a third terminal allows for flexibility in top cell material selection

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A performance comparison between GaInP-on-Si and GaAs-on-Si 3-terminal tandem solar cells

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SUMMARY
The pursuit of ever-higher solar cell efficiencies has focused heavily on multijunction technologies. In tandem cells, subcells are typically either contacted via two terminals (2T) or four terminals (4T). Simulations show that the less-common three-terminal (3T) design may be comparable to 4T tandem cells in its compatibility with a range of materials, operating conditions, and methods for subcell integration, yet the 3T design circumvents shading losses of the 4T intermediate conductive layers. This study analyzes the performance of two superstrate 3T III-V-on-Si (III-V//Si) tandem cells: One has slightly greater current contribution from the Si bottom cell (GaInP//Si) and the other has substantially greater current contribution from the GaAs top cell (GaAs//Si). Our results show that both tandem cells exhibit the same efficiency (21.3%), thereby demonstrating that the third terminal allows for flexibility in the selection of the top cell material, similar to the 4T design.

INTRODUCTION
Multijunction (MJ) solar cells are currently the only approach to photovoltaic (PV) efficiency improvement that provides a pathway toward modules that could exceed 30%. Moreover, mechanically stacked III-V-on-Si (denoted as III-V//Si) tandem cells have already achieved higher efficiencies than the theoretical efficiency limit for single-junction Si solar cells (Essig et al., 2017; Schäfer and Brendel, 2018). Within the multijunction research community, there is a growing interest in 3-terminal (3T) tandems as a hybrid approach to address challenges confronted by the more traditional 2-terminal and 4-terminal solar cell designs (Nagashima et al., 2000; Martí and Lucque, 2015; Zou et al., 2018; Djebbour et al., 2019; Rienäcker et al., 2019b; Schnabel et al., 2020; Adhyaksa et al., 2017; Santbergen et al., 2019; Jost et al., 2020; Tayagaki et al., 2020; Alshkeili and Emziane, 2014; Tockhom et al., 2020). In contrast to 2T configurations, 3T designs do not require current matching between the subcells and are robust to spectral variations (Warren et al., 2018a). The 3T configuration paired with a Si interdigitated back contact (IBC) bottom cell circumvents the 4T design requirement for additional grid lines and/or transparent laterally conductive layers at the back of the top cell and could also potentially be compatible with direct growth of III-V materials on Si (Itoh et al., 1988; Umeno et al., 1996; Vaisman et al., 2017). Device simulations show that efficiencies exceeding 30% could be achieved for III-V//Si tandem cells in the 3T configuration, comparable to 4T tandem performance (Essig et al., 2017; Warren et al., 2018a, 2020; Rienäcker et al., 2017).

Three-terminal tandems can be fabricated from different subcell materials using a transparent conductive adhesive (TCA) interconnection layer (Schnabel et al., 2020; Klein et al., 2018). In this paper, we introduce a new superstrate 3T tandem design that uses TCA to laminate a silicon IBC bottom subcell with a thin III-V top subcell processed on glass, which provides mechanical support to both subcells. Once laminated, the TCA interlayer provides a conformal and conductive interlayer between the front of the Si cell and the back of the thin film top cell. This design could potentially enable the use of textured Si IBC bottom cells, although the bottom cells reported herein are planar. These results can provide insight into how other narrow-bandgap superstrate top cell materials (e.g. CdTe/Si, perovskite/Si) might perform when coupled with Si in the 3T configuration.

This paper provides experimental verification of previously published simulations that predict the inclusion of a third terminal in a hybrid tandem solar cell can enable the extraction of surplus photocurrent from current mismatched subcells (Rienäcker et al., 2019a, 2019b; Warren et al., 2018a; Warren et al., 2020; Stradins
et al., 2019). We experimentally compare the performance of two mechanically stacked III-V/Si tandem cells: One has a wider bandgap top cell with minimal current mismatch (GaInP/Si) and the other has a narrower bandgap top cell with significant current mismatch (GaAs/Si). Our results show that both 3T tandem cells exhibit about the same efficiency (21.3%), thereby demonstrating that the inclusion of a third terminal allows for flexibility in the selection of the top cell material, similar to 4T tandem designs (Essig et al., 2017).

RESULTS AND DISCUSSION
In this paper, we report on n-on-p III-V top solar cells stacked onto IBC Si bottom cells with an n-type bulk absorber. In the terminology of the recently published taxonomy for 3TT (Warren et al., 2020), the Si IBC cell is a single (i.e. “uni”) minority carrier contact (nuIBC), forming a 3TT with subcells that have opposite doping at their shared interface (i.e. series (s) interconnection); therefore, the devices can be described concisely as III-V/s/nuIBC 3TTs.

The subcells are fabricated independently and then laminated together using a TCA containing conductive microspheres to make contact between the subcells (Klein et al., 2018). Figure 1 shows schematics of the TCA-bonded 3TT superstrate architecture, using planar Si IBC bottom cells for the a) GaInP/s/nuIBC and b) GaAs/s/nuIBC cells reported on in this study. The top and the bottom cells have an active cell area of 1.00 cm². Additional information about device fabrication is provided in the Method details.

The cell structure shown in Figure 1 is similar to the GaInP/s/nuIBC cell that achieved 27.3%, the highest reported efficiency for a 3TT cell (Schnabel et al., 2020). In contrast to the design of this recently reported cell, however, the 3T superstrate structure reported here includes front glass to mechanically support the III-V cell during fabrication. The previous cell design required that the top cell be processed after the two subcells were bonded together. Once stacked, the Si bottom cell was the thickest component of the structure so that these cells were susceptible to cracking during top cell processing and subsequent characterization.

The contacts of the III-V/s/nuIBC 3TT cell are labeled T (top of the n-type front contact of the III-V top cell), R (p-type IBC contact for an nuIBC cell), and Z (n-type IBC contact for an nuIBC cell) according to the taxonomy of (Warren et al., 2020), as shown in Figure 2. The characterization of a 3TT cell that includes an IBC Si bottom cell is more complex than that of a 2T or 4T cell because it involves two circuits with a common terminal that interact during cell operation (Schnabel et al., 2020; Warren et al., 2018a, 2018b). 3TT cells can be interconnected in three different configurations depending on which terminal is common to both circuits: Common-Z (CZ), Common-R (CR), and Common-T (CT) (Warren et al., 2020). In this study, the 3TT cells were measured in CZ configuration with the Z terminal (n-contact of the nuIBC cell) common to both circuits that were measured simultaneously (Figure 2). In the CZ measurement configuration, the TZ circuit includes the performance of the top cell in series with the internal resistances between the back of the top cell and the n-contact of the IBC circuit while the RZ circuit measures the IBC performance of the Si bottom cell. The previous 3TT results reported by (Schnabel et al., 2020) were measured in the CR configuration, with the R terminal (p-busbar of the nuIBC cell) common to both circuits. The CZ configuration provides the most direct way of analyzing the performance of the subcells because the two circuits produce power simultaneously at the global maximum power point, regardless of the current matching between cells (Tayagaki et al., 2021). Additional details about the 3TT cell characterization technique and a discussion comparing the performance of a 3TT cell measured in the CR, CZ, and CT configurations can be found in the study by Geisz et al., (2021).

We present measurements of current density-voltage (J-V) data for the two circuits in Figure 3B and 3D while controlling the state of the other circuit and analyze them in the context of the systematically varied 3TT measurements presented as power-voltage-voltage (P-V-V) plots in Figure 4. The illumination was set to 1 sun on each subcell as described in the Method details. All measurements were taken by connecting the circuits illustrated in Figure 2 to two Keithley 238 sourcemeter units with the low terminals connected at ground to the Z contact of the 3TT devices.

For three-terminal tandems, the performance of the subcells is coupled both electrically and optically, requiring careful measurement protocols (Geisz et al., 2021; Tayagaki et al., 2018). In order to quickly estimate the maximum power point (MPP) of the 3TT device, we employed the following constrained procedure that mitigates the effects of these coupling mechanisms. First, the RZ circuit is held at short circuit
(V_{RZ} = 0) while the J-V data of the TZ circuit are measured using voltage steps of 0.01 V. Then, the RZ circuit is measured with the TZ circuit constrained to V_{TZ,mpp} from the first measurement. Since luminescent coupling from the top to the bottom cell may strongly affect the photocurrent of the bottom cell, it is imperative that the RZ circuit is measured with a good estimate of the V_{TZ,mpp}. The effects of electrical coupling during the first measurement are minimized since any voltage shift at the 3TP_{max} due to a shared common Z resistor should be similar in magnitude when the RZ current is at either J_{RZ,SC} or J_{RZ,mpp} (Geisz et al., 2021). A further measurement of the TZ circuit with the RZ circuit constrained to V_{RZ,mpp} could have confirmed the estimate (Tayagaki et al., 2020). Both tandem cells, however, were damaged before such a measurement could be obtained.

The external quantum efficiency (EQE) and J-V characteristics are shown for each 3TT CZ circuit in Figure 3 with constraints indicated by brackets. A summary of the J-V data is provided in Table 1 (see Method details...
for additional information about the J-V and EQE measurements. The performance of the 3TT devices including all coupling mechanism was characterized by systematically and independently varying the voltages $V_{TZ}$ and $V_{RZ}$ in increments of 0.1 V. The corresponding currents were measured simultaneously and the power density at each point was calculated as $P = -(V_{TZ} J_{TZ} + V_{RZ} J_{RZ})$ (The negative was applied so that positive power indicates the power producing state). The resulting P-V-V plots are shown in Figure 4 with positive powers indicated by large colored points and negative powers omitted. Contours of constant power are also shown, as derived from the colored points. The point labeled “$P_{max}(TZ) + P_{max}(RZ)$’” is the $P_{max}$ obtained from summing the two
constrained J-V measurements described above (Figure 3 and Table 1). The corresponding series-connected 2T performance (point labeled “2T \(P_{\text{max}}\)”, shown in red) was characterized by measuring the voltages while varying the currents such that no current flowed through the common Z contact by constraining \(J_{TZ} = -J_{RZ}\).

As indicated in the P-V-V plots in Figure 4, the estimated \(P_{\text{max}}\) and its location \((V_{RZ,\text{mpp}}, V_{TZ,\text{mpp}})\) obtained from the constrained J-V data is consistent with, though slightly higher, than the \(P_{\text{max}}\) value obtained from the P-V-V plots, for both cells. This difference is attributable to key distinctions between the two techniques used to approximate the 3TT performance. First, the low resolution of the P-V-V data is one likely cause for the observed difference in \(P_{\text{max}}\) values. Also, the constrained J-V data were collected in seconds, whereas the P-V-V data were collected over several minutes, resulting in a reduction in voltage due to cell heating during data acquisition. Finally, the constrained estimate of the MPP was not confirmed with a third measurement of the TZ circuit with the RZ circuit constrained to \(V_{RZ,\text{mpp}}\) to confirm this quick estimate. Though likely underestimated for the reasons stated above, the \(P_{\text{max}}\) values obtained from the P-V-V plots will be used for comparison to the 2T measurements in the discussions below.

**Figure 4. P-V-V plots of both tandem cells**
Caption: 3T P-V-V plots of (A) GaInP/s/nulBC (B) GaAs/s/nulBC. The red point labeled “2T \(P_{\text{max}}\)” is the maximum power point of the series-connected 2T measurements. “P-V-V \(P_{\text{max}}\)” is the maximum of the 3T P-V-V plot. “\(P_{\text{max}}(TZ) + P_{\text{max}}(RZ)\)” is the \(P_{\text{max}}\) obtained from the constrained J-V data provided in Figure 3 and Table 1.
For the GaInP/s/nuIBC tandem cell (Figures 3A and 3B), the maximum current of $J_RZ$ (the IBC bottom cell) is slightly greater than the maximum current of $J_TZ$ (the GaInP top cell), as shown in Figures 3B and Table 1. This difference is because the bandgaps of the subcells (1.81 eV for GaInP and 1.12 eV for Si) are not ideal for a current-matched 2TT, giving rise to a top-cell-limited tandem cell when operated in 2T mode. The P-V-V plot of the GaInP/s/nuIBC tandem cell (Figure 4A) shows a 3T $P_{max}$ of 21.3 mW/cm$^2$ and a series-connected 2T $P_{max}$ of 20.8 mW/cm$^2$. The 3T configuration enables more photocurrent collection from the Si bottom cell than the 2T configuration, resulting in a power output improvement of 0.5 mW/cm$^2$. This slight difference between the 2 and 3T $P_{max}$ is what one would expect when the current mismatch between the subcells is small. It is also similar to the 2T vs. 3T $P_{max}$ difference of 0.9 mW/cm$^2$ observed for the GaInP/s/nuIBC tandem reported on in the study by Schnabel et al., (2020).

In contrast, for the GaAs/s/nuIBC tandem cell (Figures 3C and 3D), the current mismatch between the subcells is substantial. This results in a tandem cell that would be extremely current-limited by the bottom cell if operated as a 2TT. In the case of GaAs/s/nuIBC, the P-V-V plot (Figure 4B) also shows a $P_{max}$ of 21.3 mW/cm$^2$ but a series-connected 2T $P_{max}$ of 12.1 mW/cm$^2$, due to the severely current-limiting bottom cell. This results in a performance improvement of 9.2 mW/cm$^2$ when operating the GaAs/s/nuIBC tandem in the 3T mode compared to the 2T mode. These results show that current mismatched cells are not current-limited by one subcell when operated at the optimal point in the 3T configuration.

These 3T efficiencies (21.3% for both GaInP/s/nuIBC and GaAs/s/nuIBC) are considerably lower than the performance predicted by simulations (Warren et al., 2018a, 2020) or measured from comparable subcells (Schnabel et al., 2018, 2020; Rienäcker et al., 2017; Geisz et al., 2013; Haase et al., 2018). This sub-optimal performance is largely due to optical losses that could be improved by adding an ARC layer to the front side of the glass, using ITO instead of IZO at the back of the III-V top cell to reduce parasitic absorption, improving the TCA properties at the subcell interface, and further optimizing the III-V and poly-Si layers immediately adjacent to the subcell interface. A recent study details TCA synthesis and optimized lamination conditions for tandem cell fabrication (Klein et al., 2021). Further efficiency improvements could be achieved with the inclusion of textured Si IBC bottom cells, which should lead to improved optical absorption in the Si bottom cell in optimized versions of these cells.

**Conclusion**

In this study, we introduce a 3T superstrate tandem structure that provides mechanical support to the subcells. This new 3T cell design was used to fabricate two 3T III-V/Si tandem cells, one with minimal difference between subcell photocurrents (GaInP/s/nuIBC) and another with substantial difference between subcell photocurrents (GaAs/s/nu-IBC). The subcells with substantially different photocurrents exhibit a large performance improvement of 9.2 mW/cm$^2$ when operated in the 3T mode compared to the 2T mode, though the benefit is modest (0.5 mW/cm$^2$) when the subcell photocurrent difference is small (GaInP/s/nuIBC). These results support recent simulations indicating that the 3T design is similar to the 4T design by enabling a wider variety of material options for the top cell (Tockhorn et al., 2020; Warren et al., 2020; Gota et al., 2020). If successfully optimized, the 3T superstrate structure could be adapted for other narrow-bandgap thin film top cell materials (e.g. CdTe and perovskites) to enable surplus photocurrent collection from current mismatched subcells.

**Table 1. J-V data for cells in Figure 3**

| Primary Constraint | $J (mA/cm^2)$ @ $V = 0$ | $V (V)$ @ $J = 0$ | FF (%) | $P_{max}$ (mW/cm$^2$) and Eff. (%) |
|-------------------|--------------------------|------------------|--------|----------------------------------|
| $[V_{RZ} = 0]$   | $J_{RZ} = 12.6$ @ $V_{RZ} = 0$ | $V_{TF} = 1.365$ @ $J_{TF} = 0$ | 79.1   | 13.6                             |
| $[V_{TF} = V_{imp,top}]$ | $J_{RZ} = 18.0$ @ $V_{RZ} = 0$ | $V_{TF} = 0.652$ @ $J_{TF} = 0$ | 75.6   | 8.9                              |
| $[V_{RZ} = 0]$   | $J_{RZ} = 23.0$ @ $V_{RZ} = 0$ | $V_{TF} = 1.022$ @ $J_{TF} = 0$ | 79.0   | 18.6                             |
| $[V_{TF} = V_{imp,top}]$ | $J_{RZ} = 8.3$ @ $V_{RZ} = 0$ | $V_{TF} = 0.614$ [J$_{TF} = 0$] | 72.8   | 3.7                              |

Caption: J–V data (un-certified) for the III-V/s/nuIBC cells in Figure 3. Data were measured with illumination set to 1-sun at each junction. The colored text in each row below corresponds to a J–V curve of the same color in Figure 3, with symbols to identify the key points (as labeled). Cell identification details are provided in Method details.
Limitations of the study

In this paper, we compared the performance of two 3TT cells, one with minimal current mismatch (GaInP//Si) and one with significant current mismatch (GaAs//Si). Although these results demonstrate that the inclusion of a third terminal can enable the extraction of surplus photocurrent from current mismatched subcells, the limited number of cells does not permit statistical analysis. Moreover, these 3TT cells were not optimized for high efficiency. Regarding cell measurements, a more accurate estimate of the 3 TT $P_{\text{max}}$ value could have been obtained if the P-V-V data (shown in Figure 4) had been collected at higher resolution. Also, the $P_{\text{max}}$ obtained from the constrained J-V data could have been validated with a measurement of the TZ circuit, with RZ constrained to $V_{RZ,mpp}$. Unfortunately, these measurements were not possible because both tandem cells were damaged before this characterization could be conducted.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2022.104950.

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AUTHOR CONTRIBUTIONS

Conceptualization: K.T.V. and A.C.T. Methodology: E.L.W., W.E.M., M.R., K.T.V., R.P., and A.C.T. Software: J.F.G. Investigation: K.T.V., J.F.G., M.R., H.S-H., S.J., and T.R.K. Writing – original draft: K.T.V. Writing – Review and Editing: K.T.V., E.L.W., J.F.G., W.E.M., H.S-H., M.R., R.P., and A.C.T. Visualization: K.T.V., J.F.G., E.L.W., W.E.M., T.R.K., and A.C.T. Supervision: A.C.T. (Lead), J.F.G., and E.L.W. (Supporting). Project administration and funding acquisition: A.C.T. and E.L.W.

DECLARATION OF INTERESTS

Emily Warren and Adele Tamboli hold a patent related to III-V/Si tandem cells: US10256093B2. Kaitlyn VanSant is currently a NASA Postdoc Program Fellow, affiliated with NASA’s Glenn Research Center.

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Zou, Y., Zhang, C., Honsberg, C., Vasileska, D., King, R., and Goodnick, S. (2018). A lattice-matched GaNP/III-silicon tandem solar cell. In Conference Proceedings of IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC), pp. 0279–0282.
### STAR METHODS

#### KEY RESOURCES TABLE

| REAGENT or RESOURCE | SOURCE | IDENTIFIER |
|---------------------|--------|------------|
| **Chemicals, peptides, and recombinant proteins** | | |
| Trimethyl gallium | Rohm and Hass Electronics Materials | CAS-No. 1445-79-0 |
| Triethyl gallium | Sigma Aldrich | CAS-No. 1115-99-7 |
| Trimethyl indium | Rohm and Hass Electronics Materials | CAS-No. 3385-78-2 |
| Trimethyl aluminum | EMD electronics | CAS-No. 75-24-1 |
| Arsine | Air products | CAS-No. 7784-42-1 |
| Phosphine | Praxair | CAS-No. 7803-51-2 |
| Diethyl Zinc | Rohm and Hass Electronics Materials | CAS-No. 557-20-0 |
| Carbon Tetrachloride | EMD Performance Materials | CAS-No. 56-23-5 |
| Disilane: Component A | Voltaix | CAS-No. 1333-74-0 |
| Disilane: Component B | Voltaix | CAS-No. 1333-74-0 |
| Hydrogen Selenide | Air Products | CAS-No. 7783-07-5 |
| Acetone | VWR chemicals | CAS-No. 67-64-1 |
| 2-propanal | Fisher chemical | CAS-No. 67-63-0 |
| Photoresist 1818: Component A | Microposit | CAS-No. 108-65-4 |
| Photoresist 1818: Component B | Microposit | CAS-No. 1319-77-3 |
| Microposit MF319 developer: Component A | Rohm and Haas Electronic Materials LLC | CAS-No. 7732-18-5 |
| Microposit MF319 developer: Component B | Rohm and Haas Electronic Materials LLC | CAS-No. 75-59-2 |
| Nickel plating: Component A | Transene Company Inc. | CAS-No. 7718-54-9 |
| Nickel plating: Component B | Transene Company Inc. | CAS-No. 10039-56-2 |
| Nickel plating: Component C | Transene Company Inc. | CAS-No. 150-90-3 |
| Nickel plating: Component D | Transene Company Inc. | CAS-No. 7647-14-5 |
| Hydrochloric acid (HCl) | J.T. Baker | CAS-No. 7647-01-0 |
| Ammonium Hydroxide (NH4OH) | VWR Analytical | CAS-No. 1336-21-6 |
| H2O2: Component A | Fisher Scientific | CAS-No. 7722-84-1 |
| H2O2: Component B | Fisher Scientific | CAS-No. 7732-18-5 |
| Microposit CD26: Component A | Rohm and Hass Electronic Materials LLC | CAS-No. 75-59-2 |
| Microposit CD26: Component B | Rohm and Hass Electronic Materials LLC | CAS-No. 7732-18-5 |
| A2NLOF 2070 Photoresist Component A | AZ Electronic Materials USA Corp | CAS-No. 108-65-6 |
| A2NLOF 2070 Photoresist Component B | AZ Electronic Materials USA Corp | CAS-No. 67829000004- 5594P |
| A2NLOF 2070 Photoresist Component C | AZ Electronic Materials USA Corp | CAS-No. 67829000004- 5803P |
| A2NLOF 2070 MF developer: Component A | MERCK | CAS-No. 75-59-2 |
| A2NLOF 2070 MF developer: Component B | MERCK | CAS-No. 7732-18-5 |
| Phosphoric Acid - H3PO4 | Sigma Aldrich | CAS-No. 7664-38-2 |
| SU-8 2002 Component A | Microchem | CAS-No. 120-92-3 |
| SU-8 2002 Component B | Microchem | CAS-No. 89452-37-9 |
| SU-8 2002 Component C | Microchem | CAS-No. 71449-78-0 |
| SU-8 2002 Component D | Microchem | CAS-No. 108-32-7 |
| SU-8 2002 Component E | Microchem | CAS-No. 28906-96-9 |
| SU-8 developer | Kayaku Advanced Materials | CAS-No. 108-65-6 |

(Continued on next page)
**RESOURCE AVAILABILITY**

**Lead contact**

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Dr. Emily Warren (Emily.Warren@nrel.gov). E-mail addresses for all co-authors: Dr. Kaitlyn T. VanSant: Kaitlyn.VanSant@nrel.gov Dr. John F. Geisz: John.Geisz@nrel.gov Talyssa R. Klein: Talyssa.Klein@nrel.gov Dr. Steve Johnston: Steve.Johnston@nrel.gov Dr. William E. McMahon: Bill.McMahon@nrel.gov Dr. Henning Schulte-Huxel: h.schulte@isfh.de Dr. Michael Rienäcker: rienaecker@isfh.de Dr. Adele C. Tamboli: Adele.Tamboli@nrel.gov.

**Materials availability**

This study did not generate new materials.

**Data and code availability**

- Data: All data reported in this paper will be shared by the lead contact upon request.
- Code: This paper does not report original code. Further analysis of 3T tandems can be performed using https://github.com/NREL/PVcircuit.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

**METHOD DETAILS**

**Device fabrication**

Both III-V top cells were grown at NREL by organometallic vapor phase epitaxy (OMVPE) in an upright, front-junction (i.e., traditional) cell design on a sacrificial GaAs substrate (Geisz et al., 2013; Olson et al., 1990). The GaInP top cell had a 0.1 μm thick n-type emitter and a 0.9 μm p-type base. The GaAs top
cell had a 0.1 µm thick n-type emitter and a 2.8 µm p-type base (Geisz et al., 2013). A Au front grid was deposited on top of the III-V cell, the n-GaAs contact layer was removed from everywhere except the regions below the Au gridlines and an anti-reflective coating (ARC) was added. The top cell was then adhered to a glass slide with Henkel Loctite Eccobond 931-1 epoxy. Once mounted to glass, the sacrificial GaAs substrate was removed using a 1 NH₄OH:3 H₂O₂ enhant and then the GaInP stop etch was removed with HCl. A transparent conductive oxide (TCO) was sputter-deposited on the back surface of the top cell. The cell area was then defined by a mesa etch. To prevent shunting between the Au surrounding the cell area and the TCA and/or the Si bottom cell, the peripheral Au was insulated with 150 nm of MgF₂, followed by approximately 1.5 µm of Microchem SU-8 photoresist.

A TCO layer was also deposited on the front surface of the Si bottom cell. This TCO/TCA/TCO interlayer enables a conductive path between the subcells while providing anti-reflective properties. In contrast to 4T cell designs, this conductive interface enables the 3T design to circumvent the need for lateral conduction of the top cell current. For both cells reported here, indium zinc oxide (IZO) was deposited at the back of the top cell and indium tin oxide (ITO) was deposited on the front of the Si bottom cell. The optimal thicknesses of the TCO and ARC layers were modeled using PV Lighthouse’s SunSolve ray-tracer, as described in the Method details below.

The planar 3T Si bottom cells were fabricated at ISFH. The cells were made from 250 µm-thick n-type Cz-Si wafers into IBC cells with passivating doped polysilicon on oxide contacts, following the procedures outlined in Rienäcker et al. (2019b). The Si bottom cells were adapted for the 3T superstrate application by cleaving down to the Si gridline region in order to minimize the area of the Si bottom cell exposed to the Au contact of the III-V top cell, to prevent shunting.

The tandem stack was completed by laminating the subcells together at 3 psi and 110 °C for 20 min, using TCA at the interface. The TCA was synthesized using a similar technique to that described in Klein et al. (2021), where the TCA was fabricated into sheets of ethylene-vinyl acetate (EVA) with embedded Ag-coated poly(methyl methacrylate) (PMMA) microspheres (diameter range: 45–53 µm). The Ag-coated microspheres form a conductive path between the IZO-coated top cell and the ITO-coated bottom cell. Percent coverage of the Ag microspheres was estimated from an optical image of a representative region of the top cell, in which the microspheres appear as darker than the surrounding cell area. The image was filtered to digitize the light and dark regions and the percent coverage was calculated from this dark-to-light ratio (Klein et al., 2021). Previous work has indicated that excellent conductivity can be obtained from test structures with a microsphere area coverage of ≤ 1% (Klein et al., 2018) but the coverage for the cells reported here was ≈ 3.7%, likely resulting in increased shading losses to the Si bottom cell.

**Optical modeling for ARC and TCO thicknesses**

PV Lighthouse’s SunSolve ray tracing software was used to model the optical performance of the cell to determine the optimal thickness of both the anti-reflective coating (ARC) and transparent conductive oxide (TCO) layers. SunSolve is a Monte Carlo ray tracing calculator with thin film limits that uses the optical constants for each layer in a solar cell to calculate the photogenerated current. The optical constants were obtained via spectroscopic ellipsometry (SE) from individual layers of the same materials used in the solar cell itself.

Figure S1 in the supplemental information shows a simplified schematic of the 3T superstrate III-V/s/nuIBC cell assumed for modeling purposes. It should be noted that the optical modeling in SunSolve assumed both a MgF₂ ARC layer on the front-glass and textured Si for the bottom cell, but the ARC layer was not included, and planar Si bottom cells were used instead for the cells fabricated in this study.

The thickness of the ZnS and MgF₂ ARC layers were optimized first, by sweeping the possible layer thicknesses from 25–50 nm and 80–130 nm, respectively, in 5 nm increments. For GaInP/s/nuIBC, the ZnS thickness was selected to maximize the current from the III-V material, since a larger voltage can be obtained from light absorbed in the top cell. For GaAs/s/nuIBC, the selected ZnS thickness maximized the combined simulated current of both subcells. In both cases, a thin (≈ 2 nm) MgF₂ seed layer was used to adhere the ZnS to the underlying layer.

Once the optimal thicknesses for the ZnS and MgF₂ layers were determined, these values were used to model the TCO layers. Both IZO and ITO were swept between 70 and 130 nm at 10 nm increments, followed
by a second TCO simulation of the GaInP/s/nuIBC over the range of 80 nm–110 nm at 3 nm increments. The optimal thickness of the IZO and ITO layers were determined by summing the simulated $J_{sc}$ of the subcells to find the best combination for each tandem stack (GaInP/s/nuIBC and GaAs/s/nuIBC). The optimum TCO combination was very similar for both tandem cells so the same thickness of IZO (90 nm) was deposited on the back of both the GaAs and GaInP top cells and the same thickness of ITO (83 nm) was deposited on the front of their respective Si bottom cells. The optimum thickness for the ARC and TCO layers incorporated into these cells are listed in Table S1 of the supplemental information.

**3TT III-V/s/nuIBC EQE and JV characterization**

For both EQE and JV characterization, a custom inverted jig was used to characterize the superstrate 3T tandem cells since all three terminals are at the back (i.e. non-sunny side) of the glass. The jig consists of a metal platform on four legs of adjustable height with an aperture area for the cell, as illustrated in Figure S2 of the supplemental information. The superstrate 3T tandem cell was contacted using probes with a magnetic base so that, when the jig is inverted, the probes support the cell. The jig height is determined by the profile of the probes used to contact the solar cell. During EQE and JV characterization, the cell was typically held $\approx 55$–60 cm above the stage of the characterization system.

The EQE data (Figures 3A and 3C, in the main text) were measured using a custom-built system and should be considered a relative measurement, rather than absolute. The EQE data, however, were sufficient for spectral mismatch correction to achieve AM1.5G 1-sun conditions during J-V characterization. Both the J-V and P-V-V data were collected using a class A solar simulator. Calibrated reference cells were used to set the light intensity to 1-sun conditions in both subcells. The height of the solar simulator’s xenon (Xe) lamp was adjusted until the reference cell for the filtered Si bottom cell reached 1-sun. The III-V top cell irradiance was then adjusted to 1-sun with the inclusion of 470 nm blue LED light (in addition to the solar simulator illumination). A shadow mask with the aperture area of the top cell was also used to avoid stray light reaching the Si bottom cell, outside of the active III-V cell area.

The reference cells were isotypes fabricated at NREL and last calibrated in 2013. These well-matched reference cells were used with spectral mismatch corrections of (0.990; 1.001) for the GaInP//Si tandem and (1.000; 0.960) for the GaAs//Si tandem. The simulator spectrum was measured just prior to measurement with a Spectral Evolution SR-3500 spectroradiometer. III-V and silicon solar cells are known to be stable in ambient conditions, if not exposed to sustained environmental stress conditions (e.g. heat, humidity, etc.). On account of this stability, the cells were not stored under any special conditions, nor were the J-V measurements conducted under specific light soaking conditions. We do, however, note in the main text of the paper that the $P_{max}$ from the P-V-V data is likely lower than the $P_{max}$ obtained from the constrained J-V data because the constrained J-V data was collected in a few seconds, whereas the P-V-V data was collected over several minutes, which likely led to a voltage reduction associated with cell heating during P-V-V data acquisition.

**Sample identification**

The 3TT GaAs top cell was fabricated from MS407A and the 3TT GaInP top cell was fabricated from MS305C. The cleaved IBC Si bottom cell stacked with the GaAs top cell was E1_005_16_19 and the cleaved IBC Si bottom cell stacked with the GaInP top cell was E1_005_16_01. All III-V samples were grown at NREL and all Si IBC bottom cells were fabricated at ISFH.