A Framework for Comparing the Energy Production of Modules using 2-, 3- and 4-Terminal Tandem Cells

Supplemental Information

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Methodology for EHE analysis

The energy harvesting efficiency (EHE) analysis was accomplished using the optoelectronic equivalent circuit tandem models described in the SI of (Geisz et al., CRPS, 2021) and (Geisz et al., JPV, 2015). [1, 2] This general model has been distributed to the public in as open-source Python-based software called *PVcircuit* [3]. Here we neglected shunt conductance and reverse-bias breakdown; the simplified equivalent circuits are shown schematically in Figure S1. In all but the final example in the manuscript, the series resistances were also neglected. The model parameters for the example tandem cells for 2T, 3T (s-type and r-type), and 4T configurations were extracted from measurements of real tandem devices (as shown in Figure S2 and references):

1. The "CM Tandem" parameters were extracted from an s-type 3T GaInP/Si tandem device (MS305) composed of a superstrate GaInP subcell laminated with a transparent conducting adhesive (TCA) to an interdigitated back contact (IBC) cell from ISFH as described in VanSant et al., iScience, 2022. [4]
2. The "VM Tandem" parameters were extracted from a 4T GaAs/Si tandem device (MR218) composed of an inverted 1.5 µm-thick GaAs cell on glass stacked with an IBC from ISFH as described in Whitehead et al., APL, 2021. [5] The 4T device was measured and modeled as a 3T device by connecting the two subcells together in an s-type 3T configuration as suggested in Geisz, et al., Cell Reports, Physical Science, 2022. [1]
3. The "Generic Tandem" parameters were extracted from an s-type 3T GaInP/GaAs tandem device (WB417) that was grown inverted with an interconnecting tunnel junction and epoxied to glass as described in Geisz, et al., CPRS, 2021. [1]

The external quantum efficiency (EQE) of these real devices measured at room temperature (~25°C) was used to determine the subcell photocurrents under each spectrum by integration. While the temperature dependence of the photocurrent was not modeled in this EHE analysis, the temperature dependence of the two-diode model was included relative to the temperature dependence of the detailed-balance saturation current.

$$J_{0n}(E_g,T) = A_n * J_{db}^{(1/n)}(E_g,T)$$

where T is the temperature in Kelvin, E_g is the junction bandgap, n is the ideality factor, and A_n is a constant that was fit to the data at T=25°C. We use a two-diode model that includes both an n=1 diode and an arbitrary n for the second diode that is typically close to 2.0. The detailed-balance reverse-saturation current density, J_{db}, of each junction is given by.

$$J_{db}\left(E_g, T\right) = \frac{2\pi q(kT)^3}{h^3 c^2}\left[\left(\frac{E_g}{kT}\right)^2 + 2\frac{E_g}{kT} + 2\right] e^{-E_g/kT}$$

Where k is the boltzman constant, c is the speed of light, h is the plank constant, and q is the elemental charge. The luminescent coupling from the top to bottom subcell is included relative to the reciprocal relation of voltage to emitted light with a single empirical parameter (β) that characterizes the specific optical geometry of the device.

$$J_{TR}^{LC} = \beta\, J_T^{db}\left[e^{\frac{qV'_T}{kT}} - 1\right]$$

where V'_T is the voltage across the top subcell excluding any voltage drop across a series resistance. The 3T measurements of these devices were fit to the optoelectronic model as shown in Figure S2 (and the associated literature references). The resulting model parameters were used to calculate subcell JV curves under conditions of varying spectrum and temperature. In Figure S3, the modeled JV curves of the three example tandems under standard AM1.5G conditions at 25°C are shown. Here the subcell curves are calculated within an s-type 3T tandem structure with the other subcell held at short circuit.The dashed curves include the fit resistances and the solid curves set the resistances to zero as done in the simplified cases discussed in the paper.

References:

[1] J. F. Geisz, W. E. McMahon, J. Buencuerpo, M. S. Young, M. Rienäcker, A. C. Tamboli and E. L. Warren, *Cell Reports Physical Science*, 2021, **2**, 100677.

[2] J. F. Geisz, M. A. Steiner, I. Garcia, R. M. France, W. E. McMahon, C. R. Osterwald and D. J. Friedman, *IEEE Journal of Photovoltaics*, 2015, **5**, 1827–1839.

[3] *PVcircuit software*, J. F. Geisz, E. L. Warren and W. E. McMahon, 2022, https://github.com/NREL/PVcircuit, https://doi.org/10.11578/dc.20220518.1.

[4] K. T. VanSant, E. L. Warren, J. F. Geisz, T. R. Klein, S. Johnston, W. E. McMahon, H. Schulte-Huxel, M. Rienäcker, R. Peibst and A. C. Tamboli, *iScience*, 2022, **25**, 104950.

[5] R. C. Whitehead, K. T. VanSant, E. L. Warren, J. Buencuerpo, M. Rienäcker, R. Peibst, J. F. Geisz and A. C. Tamboli, *Appl. Phys. Lett.*, 2021, **118**, 183902.

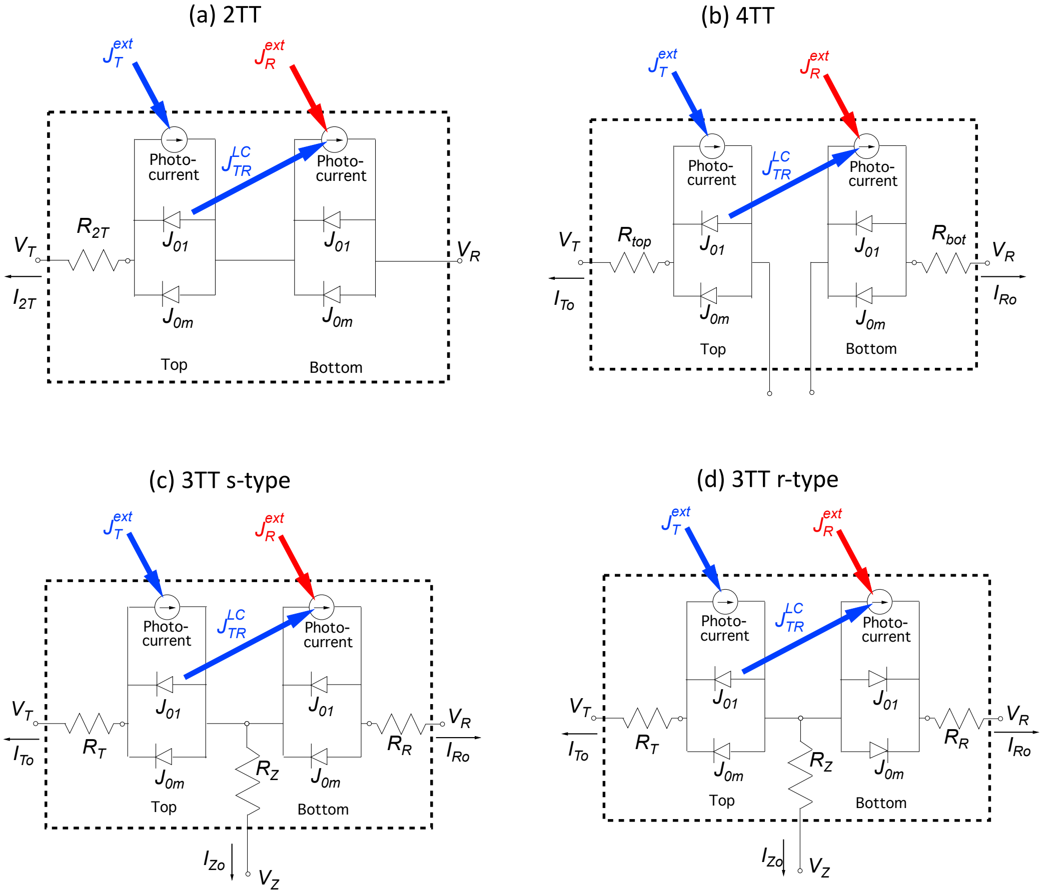

Figure S1: Schematic diagrams for the equivalent circuits used for our calculations: (a) 2T, (b) 4T, (c) s-type 3T, and (d) r-type 3T tandem cells.

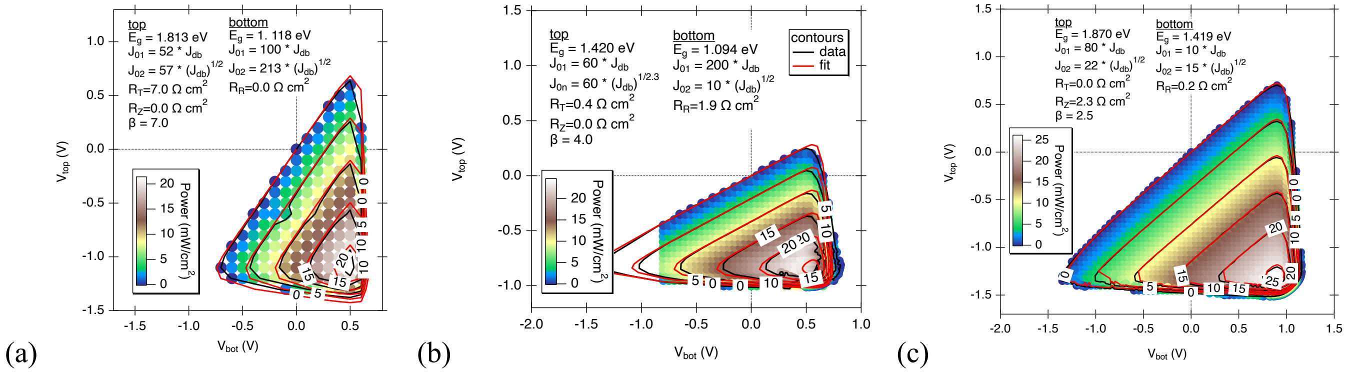

Figure S2: Experimental data and fits of 3T measurements of real tandems to determine example diode parameters. a) CM example GaInP/Si (MS305), b) VM example GaAs/Si (MR281), c) Generic example GaInP/GaAs (WB417). Colored points indicate measured power as indicated by the color scale. Black lines are the contour lines of the measured data. Red lines are the contour lines of the model fit using the inset parameters. The units of current densities are mA/cm^2.

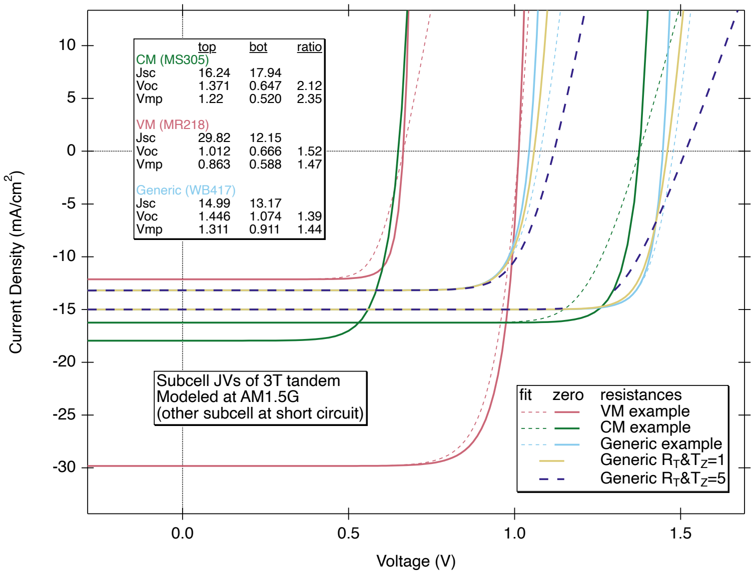

Figure S3: Modeled subcell JV curves of example 3T tandems. Each subcell curve is calculated from the model while the other subcell is held at short circuit. The dashed lines show the JV of the full model fit to the real devices, but the solid lines remove series and shunt resistances for simplicity as used in the text examples. Inset J_{SC}, V_{OC} and V_{MPP} values are for the resistance-free curves as used in the text examples. Both top and bottom junction JV curves are included in each case.

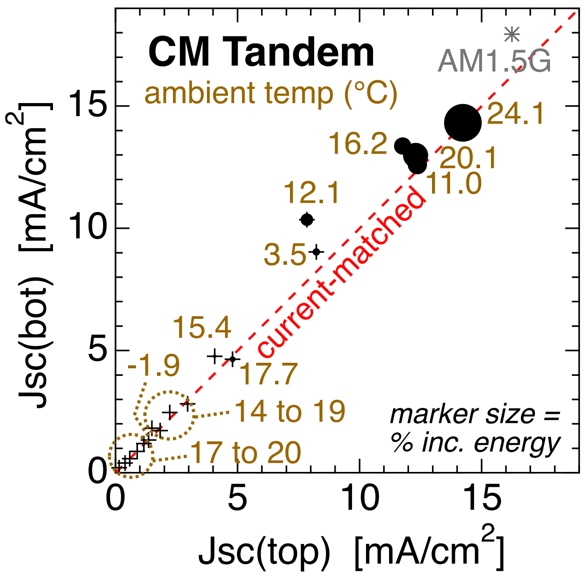

Figure S4: Temperature corresponding to each photocurrent pair produced by the CM Tandem cell under each proxy spectrum in the set of spectra used for EHE calculations. The corresponding temperature has been indicated for each spectrum or cluster of spectra, and the size of each point represents the incident energy corresponding to that spectrum (with "+" markers indicating the positions of the smaller points). Dashed circles are labeled with the temperature range for the enclosed groups of spectra.

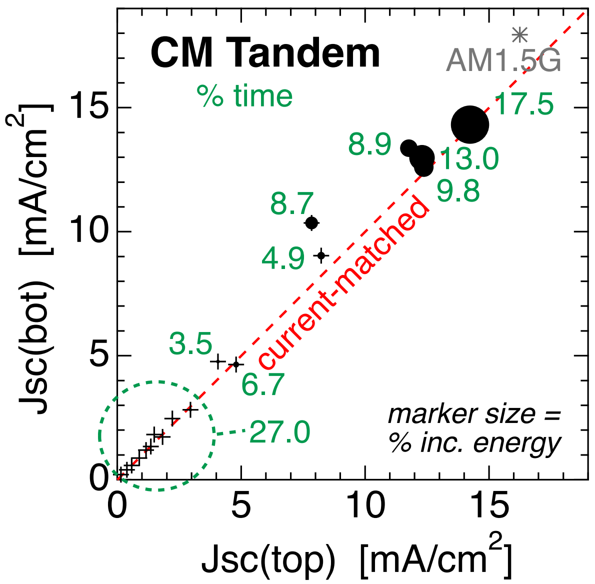

Figure S5: The percentage of daylit time corresponding to each photocurrent pair produced by the CM Tandem cell under each spectrum in the set of proxy spectra used for EHE calculations. The labels indicate the fractional time percentage (for the year) corresponding to each spectrum or cluster of spectra, and the size of each point represents the incident energy corresponding to that spectrum (with "+" markers indicating the positions of the smaller points). For an EHE calculation, the cell efficiency is computed for each spectrum, then the resulting efficiencies are averaged weighted by their fractional times to give an EHE for the total time period (one year, in this case).