Supplementary Information

Thorough subcells diagnosis in a multi-junction solar cell via absolute electroluminescence-efficiency measurements

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Contents:

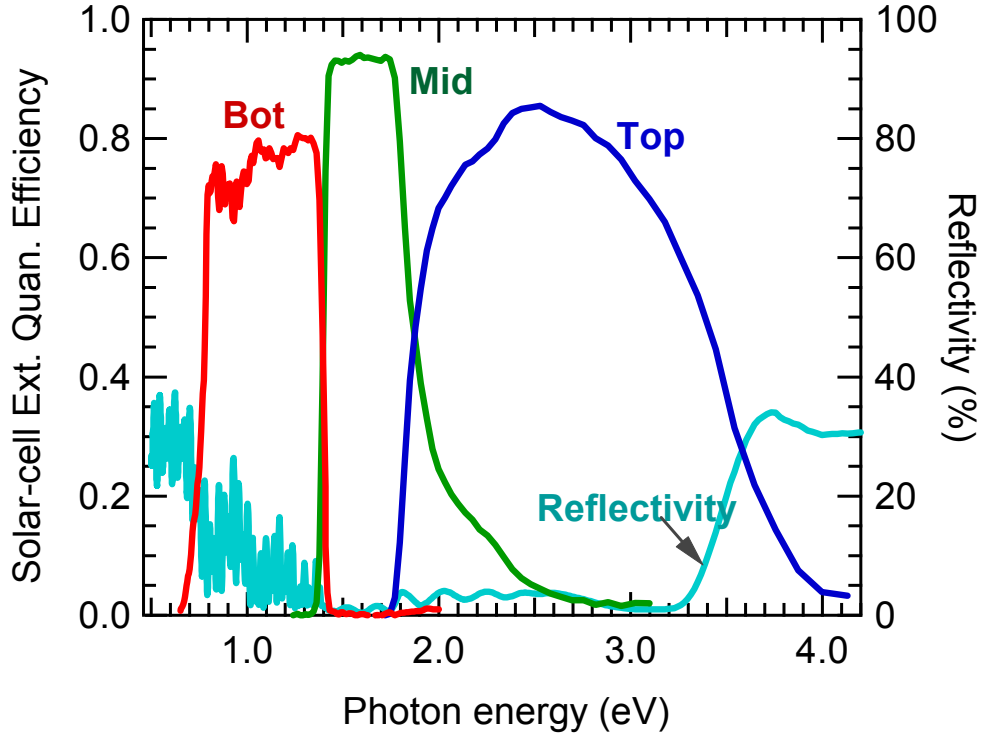# I. Solar-cell external quantum efficiency of the tandem solar cell

Figure S1. Solar-cell EQE and reflectivity spectrum of the GaInP/GaAs/Ge 3-junction solar cell. EQE measurements were performed with a commercial spectral response measuring equipment. The EQE of the bottom cell was calibrated according to the method proposed by G. Siefer et al. [Ref.S1]. The reflectivity of the solar cell was measured with a spectrophotometer (JASCO-V570).

Ref.S1: Siefer, G., Baur, C. & Bett, A.W. External quantum efficiency measurements of germanium bottom subcells: measurement artifacts and correction procedures, Proceedings of the 35th IEEE Photovoltaic Specialists Conference, 704–707 (2010).

Table S1. Definitions and values of the essential parameters for calculations.

Parameters	Top subcell	Middle subcell	Bottom subcell
Band-gap E_{g_i} (eV)	1.810	1.405	0.690
Refractive index n_i	3.50	3.55	4.00
$<EQE_i>_{EL} = \int EQE_i(E)S_{EL}(E)dE / \int S_{EL}(E)dE$	0.35	0.86	0.15

II. Balance sheets of carrier and energy of subcells in the tandem solar cell under various operation conditions

Abbreviations: TR: transmission loss, TH: thermalization loss, EM: external emission loss, NR: non-radiative recombination loss, JN: junction loss, LC: luminescent coupling.

Table S2a. Carrier balance sheet for open-circuit condition (J = 0, V = V_{oc}) with 1-sun AM0.

Cell	Input (Ratio)		Loss (Ratio)			Output (Ratio)
	AM0 1Sun	LC	EM	LC	NR	
Top	1.00	—	8E-04	0.01	0.989	0
Middle	1.00	0.01	0.009	0.12	0.881	0
Bottom	1.00	0.081	8E-05	—	1.081	0

Table S2b. Carrier balance sheet for open-circuit condition (J = 0, V = V_{oc}) with 1-sun AM0. Unit: mA/cm^2.

Cell	Input (mA/cm^2)		Loss (mA/cm^2)			Output (mA/cm^2)
	AM0 1Sun	LC	EM	LC	NR	
Top cell	17.136	—	0.014	0.173	16.949	0.000
Middle cell	17.916	0.173	0.169	2.13	15.791	0.000
Bottom cell	26.434	2.13	0.002	—	28.562	0.000

Table S3a. Energy balance sheet for open-circuit condition (J = 0, V = V_{oc}) with 1-sun AM0.

Cell	Input (Ratio)		Loss (Ratio)					Output (Ratio)
	AM0 1Sun	LC	TH	EM	LC	NR	JN	
Top	0.305	—	0.076	2E-04	2E-03	0.227	0	0
Middle	0.224	2E-03	0.038	2E-03	2E-02	0.164	0	0
Bottom	0.207	2E-02	0.083	1E-05	—	0.146	0	0
TR loss	0.264	—	—	—	—	—	—	—
Total	1.000	2.4E-02	0.197	2.0E-03	2.4E-02	0.537	0	0

Table S3b. Energy balance sheet for open-circuit condition (J = 0, V = V_{oc}) with 1-sun AM0. Unit: mW/cm^2.

Cell	Input (mW/cm^2)		Loss (mW/cm^2)					Output (mW/cm^2)
	AM0 1Sun	LC	TH	EM	LC	NR	JN	
Top	41.21	—	10.197	0.026	0.314	30.678	0	0
Middle	30.22	0.314	5.117	0.237	2.993	22.186	0	0
Bottom	27.97	2.993	11.252	0.001	—	19.708	0	0
TR loss	35.60	—	—	—	—	—	—	—
Total	135.00	3.307	26.566	0.264	3.307	72.572	0	0

Table S4a. Carrier balance sheet for maximum-output-power condition ($J = J_m$, $V = V_m$) with 1-sun AM0.

Cell	Input (Ratio)		Loss (Ratio)			Output (Ratio)
	AM0 1Sun	LC	EM	LC	NR	
Top	1.00	—	5E-06	6E-05	0.025	0.975
Middle	1.00	6E-05	3E-05	4E-04	0.067	0.933
Bottom	1.00	3E-04	2E-05	—	0.368	0.632

Table S4b. Carrier balance sheet for maximum-output-power condition ($J = J_m$, $V = V_m$) with 1-sun AM0. Unit: mA/cm^2.

Cell	Input (mA/cm^2)		Loss (mA/cm^2)			Output (mA/cm^2)
	AM0 1Sun	LC	EM	LC	NR	
Top	17.136	—	9.04E-05	0.001	0.426	16.709
Middle	17.916	0.001	5.50E-04	0.007	1.201	16.709
Bottom	26.434	0.007	5.32E-04	—	9.732	16.709

Table S5a. Energy balance sheet for maximum-output-power condition ($J = J_m$, $V = V_m$) with 1-sun AM0.

Cell	Input (Ratio)		Loss (Ratio)					Output (Ratio)
	AM0 1Sun	LC	TH	EM	LC	NR	JN	
Top	0.305	—	0.076	1E-6	2E-05	0.006	0.072	0.152
Middle	0.224	2E-05	0.037	6E-6	7E-05	0.012	0.067	0.107
Bottom	0.207	7E-05	0.072	3E-6	—	0.050	0.057	0.028
TR loss	0.264	—	—	—	—	—	—	—
Total	1.000	9E-5	0.185	1E-5	9E-5	0.068	0.196	0.287

Table S5b. Energy balance sheet for maximum-output-power condition ($J = J_m$, $V = V_m$) with 1-sun AM0. Unit: mW/cm^2.

Cell	Input (mW/cm^2)		Loss (mW/cm^2)					Output (mW/cm^2)
	AM0 1Sun	LC	TH	EM	LC	NR	JN	
Top	41.21	—	10.197	1.6E-4	0.002	0.771	9.685	20.558
Middle	30.22	0.002	5.047	7.7E-4	0.010	1.687	9.083	14.394
Bottom	27.97	0.010	9.735	3.7E-4	—	6.715	7.743	3.786
TR loss	35.60	—	—	—	—	—	—	—
Total	135.00	0.012	24.979	1.3E-3	0.012	9.173	26.511	38.738

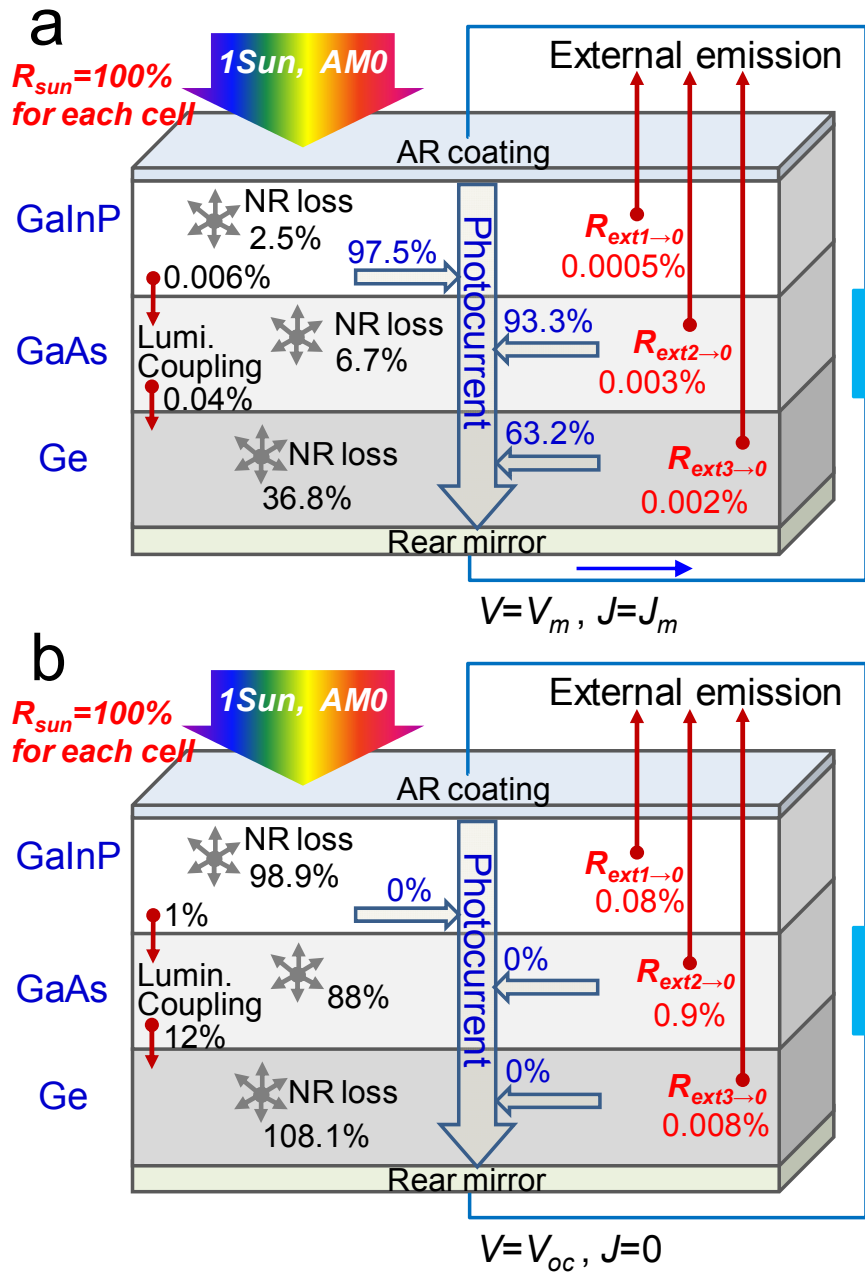## III. Carrier balance diagrams of the tandem solar cell under various operation conditions

Figure S2. **Carrier balance diagrams of solar cell with an irradiation condition of AM0 1Sun.** (a) under maximum-output-power working condition and (b) under open-circuit working condition. The input ratios of carriers for all the subcells are normalized to 1, and all the values of the given parameters are ratio.