Subcell Coupling in Tandem Solar Cells: Measurements and Modeling

John F. Geisz\textsuperscript{1}, William E. McMahon\textsuperscript{1}, Jeronimo Buencuerpo\textsuperscript{1,2}, Michael Rienäcker\textsuperscript{3}, Adele C. Tamboli\textsuperscript{1}, Emily L. Warren\textsuperscript{1}

\textsuperscript{1}National Renewable Energy Laboratory (NREL), Golden, CO, USA
\textsuperscript{2}Currently at L’Institut Photovoltaïque d’Ile-de-France (IPVF), Palaiseau, France
\textsuperscript{3}Institute for Solar Energy Research Hamelin (ISFH), Emmerthal, Germany

Tandem measurements
- ALWAYS control or characterize BOTH subcells e.g. measure bottom $I_{sc}$ with top at OC & SC
- Information comes from light, current and voltage
- More terminals provides flexibility for characterization and power optimization

\[ J_{ext} = \int_{0}^{\infty} EQE(\lambda) \phi(\lambda) d\lambda \]
\[ J_{em} = J_{0b} e^{(-eV_{oc}/kT)} - 1 \]
\[ J_{0b} = \beta J_{m} e^{(-eV_{oc}/kT)} - 1 \]

Light-powered by python-based open-source
https://github.com/NREL/PVcircuit

Tandem subcells ARE NEVER INDEPENDENT!
Number of terminals changes limitations

- Electrical coupling
- Optical coupling

2T: Series current limitation
- Luminescent coupling

3T: Common resistance
- Luminescent coupling

4T: Potential shunt
- Luminescent coupling

If a subcell has a voltage
- it emits light (more prominent for good emitters like III-Vs and Perovskites)
If it emits light
- the tandem has luminescent coupling
- LC is up to $\beta = 4n^2$ times the emitted light

Tandem modeling powered by python-based open-source
https://github.com/NREL/PVcircuit

Coupled dark IV curves are sensitive for fitting model