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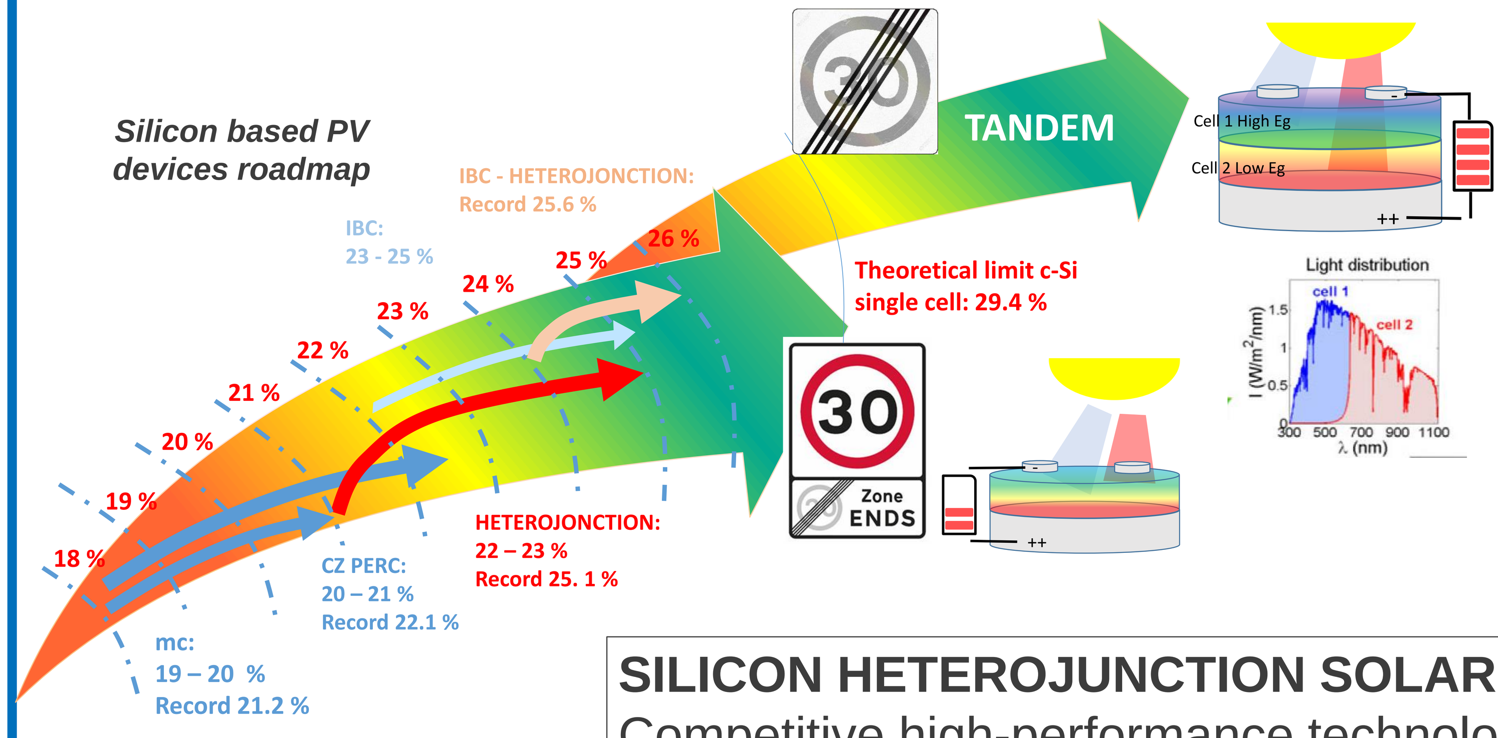
# GaInP/Silicon dual junction solar cell with 29.8 % certified record efficiency

M. DESPEISSE[1], S. ESSIG[2], C. ALLEBE[1], M. A. STEINER[2], J. F. GEISZ[2], B. PAVIET-SALOMON[1], S. WARD[2], A. DESCOEUDRES[1], L. BARRAUD[1], V. LASALVIA[2], N. BADEL[1], J. CHAMPLIAUD[1], A. FAES[1], J. LEVRAT[1], A. TAMBOLI[2], P. STRADINS[2], D. L. YOUNG[2], C. BALLIF[1].

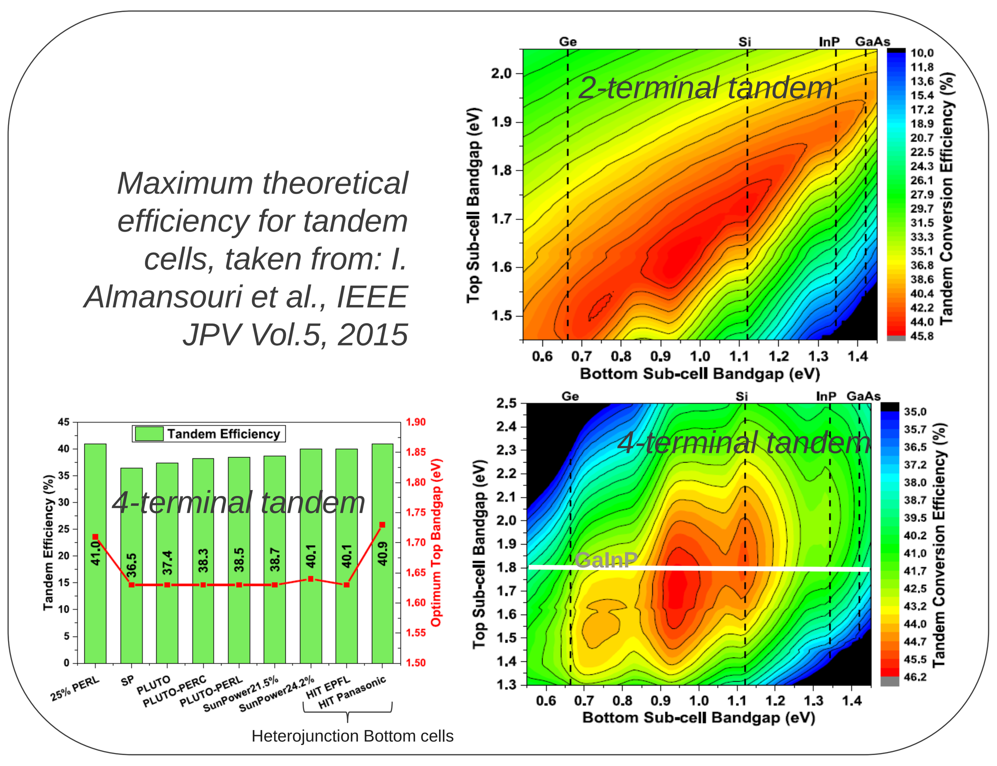
[1] *PV-Center, Centre Suisse d'Électronique et de Microtechnique (CSEM), CH-2002 Neuchâtel, Switzerland.*
[2] *National Renewable Energy Laboratory (NREL), Golden, Colorado, USA.*

## From Silicon Heterojunction Solar Cells towards Silicon Based Tandem Cells




### TANDEM SOLAR CELLS:

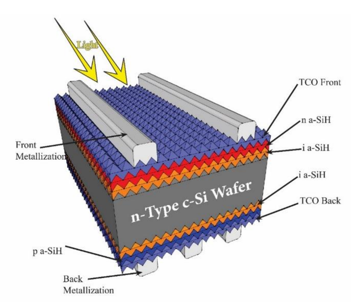
- Combination of high band-gap (1.5 -1.8 eV) top cell with low band-gap (0.8 -1.2 eV) bottom cell.
- Short-wavelength photons converted in top cell, reducing thermalization losses, yielding additional voltage. Long-wavelength photons non-absorbed below the bandgap of top cell, absorbed in bottom cell.
- Top cell materials investigated by PV community for combination with Silicon bottom cell:
  **PEROVSKITE materials**
  **III-V semiconductor materials**




*Maximum theoretical efficiency for tandem cells, taken from: I. Almansouri et al., IEEE JPV Vol.5, 2015*

### SILICON HETEROJUNCTION SOLAR CELLS:

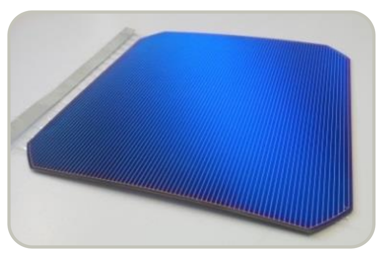
Competitive high-performance technology, ideally suited for tandem integration



*Silicon Heterojunction solar cell typical architecture*

- **Simple processing sequence**
- **High conversion efficiency (**22.8 % on CSEM platform on 156 × 156mm² full wafer n-Cz cell, measured w. GridTouch)
- **Compatible with thin wafers** (100 µm) without performance loss
- **Key advantages in the field for low LCOE: low temperature coefficient** (-0.2 to -0.25 %/ºC ), **bifacial.**

*R&D silicon heterojunction platform set up in CSEM*



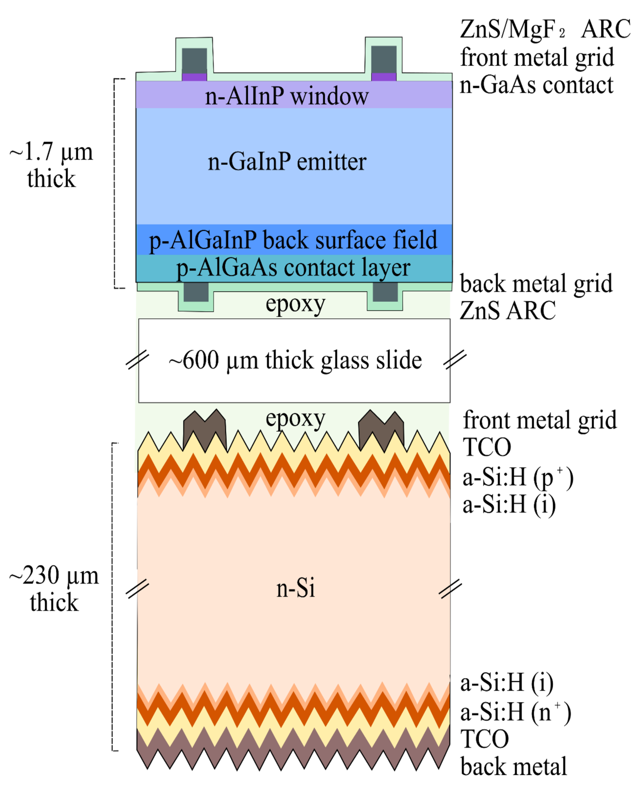
| SHJ CELL | VOC mV | FF % | JSC mA/cm² | EFF % |
|---|---|---|---|---|
| Full 6" PS n-type Cz 160 µm | 736 | 79.8 | 38.8 | 22.8 |

*Measured with GridTouch®*

## GaInP/Silicon Heterojunction TANDEM CELL

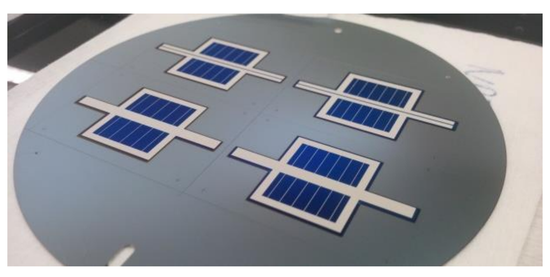
### Experimental Details:

**NREL GaInP top cell:**
1.7 µm thick rear-heterojunction GaInP with active area of ~ 1 cm² grown by MOVPE on a GaAs substrate. Gold back contact grid electroplated and ZnS ARC layer evaporated on the cell backside. Sample glued to a glass slide, and GaAs growth substrate removed. Front gold contacts electroplated, n-GaAs contact layer etched in the regions without front metal, and $ZnS/MgF_2$ dual-layer anti-reflection coating evaporated.



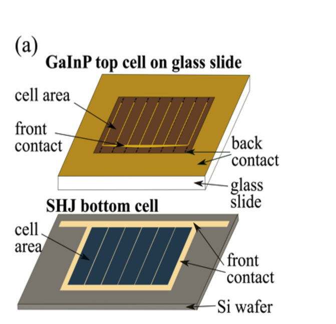

*Architecture of the GaInP/Si tandem cells developed by NREL/CSEM*

**CSEM Silicon Heterojunction bottom cell:**
a-Si:H deposited on 230 µm thick n-Fz wafer: intrinsic/n-type doped on the rear, intrinsic/p-type doped on the front, TCO layers on both sides, rear Ag sputtering, front printed metallization grid. Special TCO patterning and metallization grid designed for enabling efficient coupling to the GaInP top cell area and glass substrate dimension.



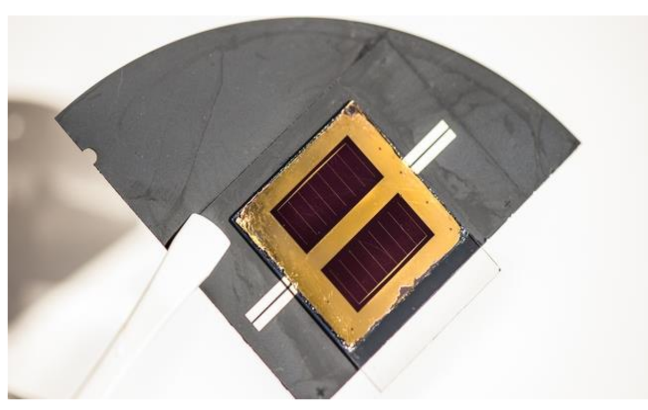
*> 1 cm2 CSEM Silicon heterojunction solar cells patterned for integration with NREL GaInP top cells.*

**GaInP/SHJ tandem:**
GaInP/Si tandem devices formed by stacking the glass slide with the top cell glued to it onto the bottom cell using a transparent adhesive. Alignment of the two subcells verified using infrared reflection before curing the adhesive.



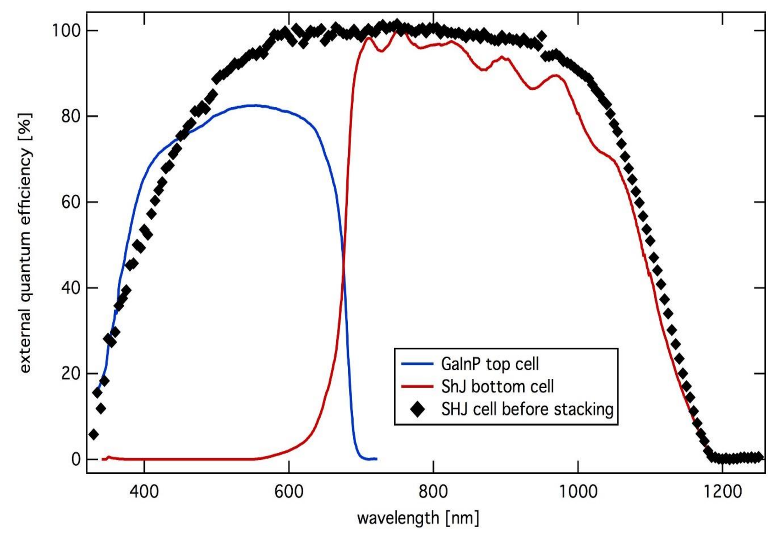

*Schematic of the 4-terminals tandem cell construction.*

The resulting tandem cells are 4-terminal mechanically-stacked GaInP/Si tandem cells.



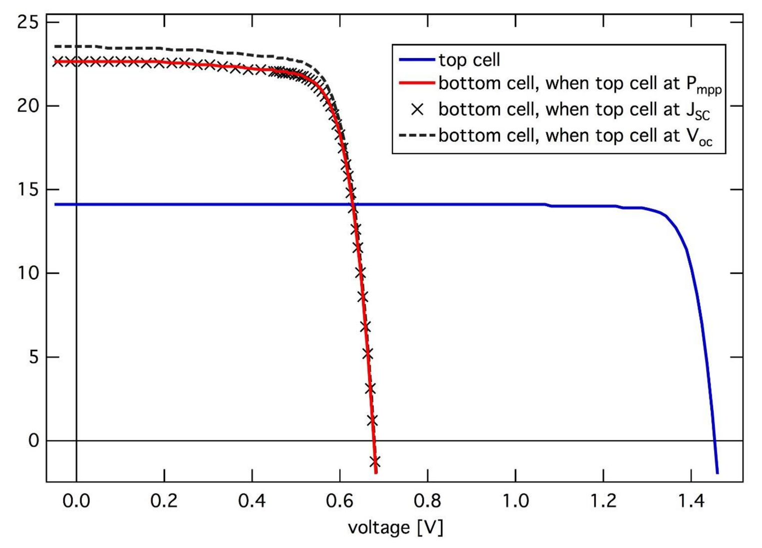
### RECORD EFFICIENCY:

**Optical Analysis:**
GaInP top cell with higher EQE than SHJ bottom cell for wavelengths < 450 nm, however with EQE limited to 83% (limited diffusion length in GaInP absorber and parasitic absorption in AlInP window layer).
Optical coupling optimization in the tandem and low top cell sub-bandgap absorption enable for high EQE in the bottom cell. Oscillations in EQE due to interferences caused by the top cell.




*Normalized External Quantum Efficiency of the GaInP/Si tandem device*

**J-V characteristics:**
Certified J-V curves measured at NREL, under AM1.5g spectral condition at 1 sun.
Top cell: $J_{SC}$ of 14.2 mA/cm², $V_{OC}$ of 1.456 V for efficiency of (18.1± 0.5)%.
Bottom cell: Luminescent coupling tested with bottom cell measured for top cell operating at $J_{SC}$, $P_{mpp}$ and $V_{OC}$. $J_{SC}$ in the Si bottom cell 0.8 mA/cm² larger when the top cell is at $V_{OC}$ than at $J_{SC,}$ due to radiative recombination in top cell. Accurate analysis of the cumulative tandem cell efficiency requires bottom cell JV-curve measured with top cell at its maximum power point.
Bottom cell generates $J_{SC}$ of 22.7 mA/cm² and $V_{OC}$ of 677 mV reaching efficiency of (11.7 ± 0.4)% in the tandem device.




*NREL certified current-voltage characteristics of the GaInP top cell and Si bottom cell of our tandem device, with an illuminated area of $A_{tandem}$ =1.006 cm². The JV-curve of the bottom cell was measured while the top cell was at $V_{OC}$, $J_{SC}$ or $P_{mpp}$*

| cell | $J_{SC}$ [mA/cm²] | $V_{OC}$ [mV] | FF [%] | eff. [%] |
|---|---|---|---|---|
| GaInP top cell | 14.15 | 1456 | 87.9 | 18.1 ± 0.5 |
| bottom cell when top cell at $V_{OC}$ | 23.53 | 678 | 75.9 | 12.1 ± 0.4 |
| bottom cell when top cell at $J_{sc}$ | 22.68 | 677 | 76.0 | 11.7 ± 0.4 |
| bottom cell when top cell at $P_{mpp}$ | 22.70 | 677 | 76.2 | 11.7 ± 0.4 |
| | | | **cumulative eff.** | **29.8 ± 0.6** |

*Certified results*

**Tandem performance:**
The 4-terminal mechanically-stacked GaInP/Si tandem cell shows certified cumulative tandem cell efficiency of (29.8 ± 0.6)%. This is the III-V/Si multi-junction solar cell with the highest one-sun efficiency, exceeding the theoretical efficiency limit 29.4% and the record experimental efficiency value 25.6% of a Si single-junction, 1-sun solar cell and exceeding record efficiency 1-sun GaAs device (28.8%).

**Perspectives:**
This first joint development highligthed limitations that can be overcome. For the bottom cell, low $V_{OC}$ due to process-induced degradation during fabrication: +10-40 mV can be expected, > 700 mV in the tandem configuration (i.e. at 23 mA/cm² instead of 39 mA/cm²). $J_{SC}$ in the Si bottom cell is 0.7 mA/cm² smaller than the maximum photon current calculated. Current in the top cell can be optimized (maximum EQE shifted up). Overall, efficiencies > 30% are potentially achievable with our tandem cell design in short-term.

**29.8 % Certified Efficiency**

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