The Evolution of High-Efficiency Multijunction Concentrator Solar Cells: A Review

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Introduction & Objective

As finite resources continue to diminish in response to the growing demand for energy, it becomes imperative to explore other more sustainable forms of energy. Solar energy has remained a promising energy alternative since its conception. Further research must be done in order to realize the industry's full potential.

Solar cell: a semiconductor device that converts sunlight into electricity; no pollutants

- Can be made of one semiconductor layer (single junction) or several (multijunction, MJ)

Concentrator Photovoltaics (CPV) uses optics to direct concentrated sunlight onto MJ cells; highly efficient

The objective of this presentation is to provide a broad survey on the R&D of CPV technology in order to understand

i. its purposes
ii. how it has evolved
iii. why its implementation was necessary

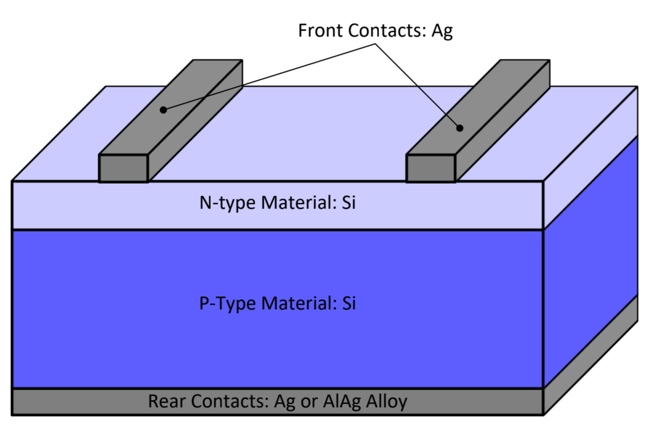

Figure 1: Single-junction silicon solar cell architecture

Methodology

In this work, different CPV architectures are compared, focusing chiefly on the effects of the following factors on efficiency:

i. number of junctions
ii. material makeup
iii. fabrication methods
iv. concentrator technology

Literature reviewed were primarily acquired from ScienceDirect, AIP Publishing, and IEEE Xplore with the assistance of AI. Papers were chosen based on the highest efficiencies of its respective decade, as well as any relevant papers to the technologies utilized.

Conclusion

- Multijunction solar cells have dramatically pushed the limits of what was thought possible with photovoltaic technology.
- Much of the efficiency gain has come as a result of manufacturing process refinement
- Efficiencies surpass 47%, and they prove to be a viable solution for addressing our energy concerns
- As the efficiency of the cells improves, the effective cost decreases
- 6 junction cells allow for the greatest efficiency and capability for power generation, but have a high manufacturing cost
- 4 junction cells are the most economically viable in terms of efficiency to manufacturing cost
- CPV will become more competitive as the optics become leaner, more reliable, and cheaper to integrate

References

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<1980 Foundational Era	1980s Early Multijunction Cell Era	1990s Optical Architecture Era	2000s Breakthrough Era	2010s Commercialization-pressure Era	2020s Ultra-high-efficiency Era
Scientific Context • Selenium-based solar cell ∘ First CPV (Fritts 1883) • Conductivity-based efficiency	**Scientific Context** • Efficiency limited by: ∘ Nonoptimized band gap ∘ Layer thickness (Bedair et al. 1979)	**Scientific Context** • Growing interest in 3J solar cells • InGaAs or Ge considered for bottom cell (MacMillan et al. 1989)	**Scientific Context** • Effort in one-sun conc. until 2004 • GaInP takes prominence as top cell material	**Scientific Context** • Capital interest in CPV systems grow • Focus in optimizing CPV architecture to reduce costs	**Scientific Context** • NREL proposes 6J CPV (Geisz et al. 2018) • Main goal is to overcome 50% eff. barrier
Multi-junction (MJ) evolution • First model of 2J cell (AlGaAs/GaAs) • Efficiency*: 10-15% (Bedair et al. 1979)	**Multi-junction evolution** • Experimental AlGaAs/GaAs cells were fabricated • Improved eff. by using MOCVD growth, widening band gap difference and mitigating reflection losses • Efficiency: 27.6% (Virshup et al. 1989)	**Multi-junction evolution** • First GaInP cell is fabricated (Olson et al. 1990) • InGaAsP bottom cell (Chung et al. 1991) • GaAs/GaSb CPV provides highest eff. • Efficiency: 35.8% (Fraas et al. 1990)	**Multi-junction evolution** • Metamorphic (MM) cells allow for higher band gap (King et al. 2003) • MM GaInP/GaInAs/Ge CPV yield highest eff. • Efficiency: 41.1% (Dimroth et al. 2009)	**Multi-junction evolution** • Dilute nitride subcells, bifacial epigrowth, & inverted MM cells allow higher eff. [83] [93] • Wafer bonding allows 4J solar cell fabrication • Efficiency: 46.1% (Ochoa 2016)	**Multi-junction evolution** • First 6J cell achieves 2nd highest eff. 46.1% (Geisz et al. 2020) • 4J cell - highest eff. ∘ Stack of 2J cells ∘ Precise analyses and MOVPE allowed high-quality materials (Helmers et al. 2024) • Efficiency: 47.6% (Dimroth et al. 2022)
Concentration/Optics • Mostly hypothetical <1975 • Reflective, refractive, and luminescent concentrators explored in late 1970s (Swanson 2000)	**Concentration/Optics** • Mirrors and simple concentrators (Ittner III 1980) • Prioritized workable concentration and system feasibility	**Concentration/Optics** • Fresnel lenses, CPCs, V-troughs, parabolic troughs, dish systems, kaleidoscope homogenizers (Chong et al. 2013) • Pivoted towards flux uniformity and widening acceptance angle	**Concentration/Optics** • Multi-stage non-imaging imaging optics • HCPV matures and concentration ratios reach upwards of 1000 suns (Feuermann and Gordon 2001)	**Concentration/Optics** • Secondary optical elements (Wiesenfarth et al. 2015) • Commercial optimization, reliability, and cost pressure • >3000 sun design (Shanks et al. 2018)	**Concentration/Optics** • CPV niche focus • Hybrid CPV/PV (Martinez et al. 2022) • Tracking-integrated CPV (Ceballos et al. 2023) • Advanced coatings (Leoga et al. 2023)
Era Takeaway • Established foundations for PV technology • First tandem cell was fabricated to realize the implications of multijunction solar cells • Primarily theoretical	**Era Takeaway** • Tandem cell surpasses single junction eff. under one-sun • Optimizing cells for high concentration is theoretically explored	**Era Takeaway** • GaAs/GaSb concentrator cell proves optics importance in high-eff. cells • First 3J solar cell (Chung et al. 1990) • Make concentrated light usable by a PV cell	**Era Takeaway** • Triple junction cells dominate due to high eff. from metamorphic cell architectures • High-efficiency cells shifted the burden toward optics and tracking	**Era Takeaway** • Cell manufacturing and architecture is optimized • CPV economics start to matter • Higher eff. → lower cost • Further development in 3J and 4J cells	**Future Considerations** • Great potential in space • Too costly for terrestrial use ∘ Need to limit optics and cell manufacturing $$$ • Cooling systems to maintain eff. • Optimize absorption and minimize shading losses

CPV Efficiency Evolution

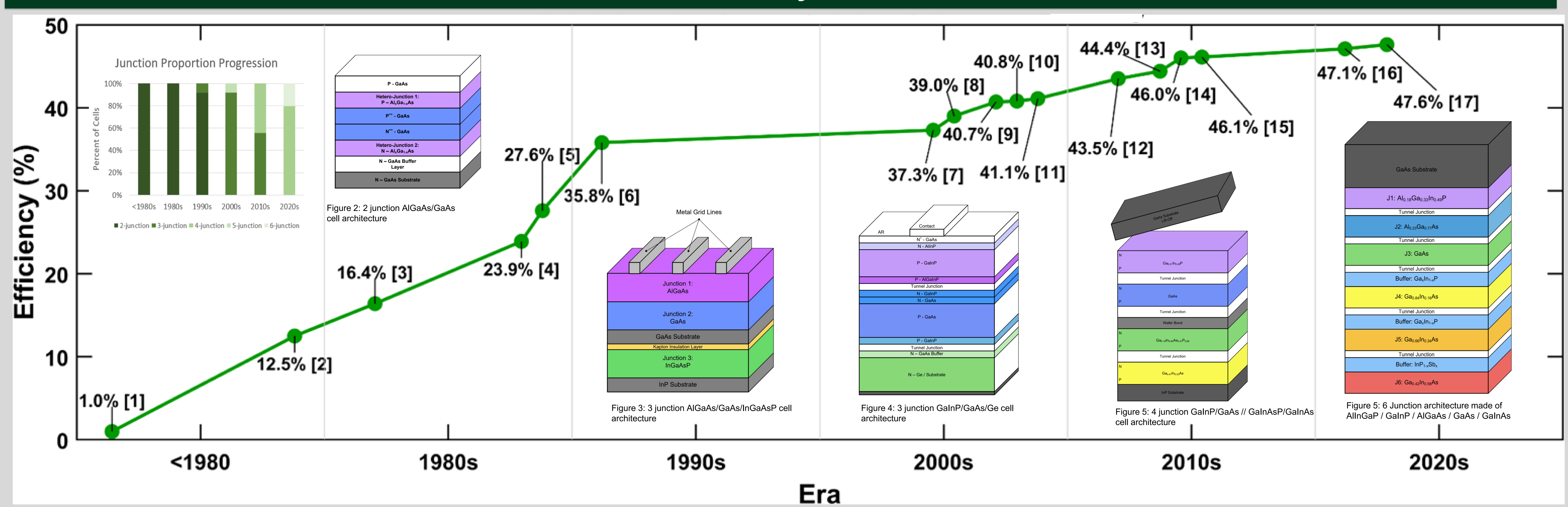

Figure 2: 2 junction AlGaAs/GaAs cell architecture

Figure 3: 3 junction AlGaAs/GaAs/InGaAsP cell architecture

Figure 4: 3 junction GaInP/GaAs/Ge cell architecture

Figure 5: 4 junction GaInP/GaAs // GaInAsP/GaInAs cell architecture

Figure 5: 6 Junction architecture made of AlInGaP / GaInP / AlGaAs / GaAs / GaInAs