PHY6004 | Introduction to Photovoltaics

A Review of the Space PV Technologies

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INTRODUCTION

Photovoltaic devices play a pivotal role in ensuring that space missions, satellites, and the International Space Station (ISS) operate seamlessly in the harsh and demanding environment of outer space. In photovoltaics, optimizing the performance triangle of power conversion efficiency (PCE), stability, and cost of production drives ongoing research. In the same and specific sense, the key factors in space photovoltaics are:-

- High Efficiency
- Radiation Resistance
- Durability
- Lightweight Design
- Advancements in Technology
- Evolving Regulations and Sustainability.[1]

The history of space photovoltaics reveals a gradual increase in efficiency, shifting from silicon-based cells in the late 1950s to the adoption of III-V multijunction solar cells in the

1990s.[2] The introduction of triple-junction cells using Gallium Indium Phosphide (GaInP), and Gallium Arsenide (GaAs) marked a significant advancement.

Notably, III-V semiconductors-based multijunction PV technologies have boosted efficiency and enhanced performance. Specifically, GaAs-based multijunction photovoltaic cells dominate space photovoltaics for their excellent radiation resistance and efficiency. Additionally, thin-film and flexible solar cells have opened up new possibilities for power generation on small satellites.

THE EXISTING SPACE PV TECHNOLOGIES

The primary PV technologies used in space are silicon and multijunction solar cells, including materials like Ge and III-V semiconductors (e.g., GaAs, InP, and their alloys). Multi-junction PV technologies, such as InGaP/InGaAs/Ge triple junction and AlInGaP/AlInGaAs/InGaAs/Ge four-junctions showcase high PCE of up to 32% initially and 28.7% after radiation exposure.[1][2]

Despite their high performance, multi-junction III-V PV technologies have drawbacks, including rigidity, thickness (80 to 200 μm)[1], weight, and complex fabrication processes. Research is now focused on cost-effective alternatives. Current highly efficient single-junction Si-based heterojunctions with intrinsic thin layer (HIT) PV devices with a PCE of 26.1%[1][2] have been proposed, making them suitable for short missions. However, Si-based PVs are nonflexible, heavy, and expensive.

$Cu(In,Ga)Se_2$ (CIGS) thin film-based PVs, with their high radiation resistance and lightweight nature (specific power of approximately 3 W g^{-1})[1], offer the potential for the next generation of space missions. They can be manufactured on flexible substrates using cost-effective techniques, simplifying spacecraft design. Despite their advantages, CIGS-based PVs have a relatively lower PCE of 23.4%.[1][2]

In recent years, hybrid organic-inorganic perovskites, like $CH_3NH_3PbI_3$ ($MAPbI_3$), have shown promise with a PCE of up to 25.5%.[1] They are attractive for space applications due to low-cost solution processing, flexibility, lightweight construction (thickness <5 μm, specific power of 23 W g^{-1}, the highest among PV technologies), and excellent radiation resistance.[1][5]

Despite their inflexibility and weight (0.4-0.8 W g^{-1})[1], multi-junction PVs, which rely on III–V semiconductors, are the primary choice for space PV technologies due to their exceptional performance (commercially available with around 32% PCE)[1][2] and remarkable resilience to radiation (maintaining PCE at approximately 87-90% following exposure to electron or proton irradiation)[1][3]. At present, the cutting-edge technology for space applications in photovoltaics is represented by the triple junction composed of $Ga_{0.50}In_{0.50}P/Ga_{0.99}In_{0.01}As/Ge$ on a Ge substrate.[1][2]

Nonetheless, creating these multi-junction devices presents significant challenges, which include the requirement for high-grade crystalline materials and the complexities associated with depositing multiple light-harvesting layers seamlessly on top of one another. While multijunction III-V solar cells can be produced through molecular-beam epitaxy (MBE) techniques, the standard practice for manufacturing commercial-scale GaInP/GaInAs/Ge devices is to employ large metal-organic chemical-vapor deposition (MOCVD) reactors.[1][2]

However, even though all the materials in this triple junction are nearly perfectly lattice-matched (LM), there is a significant issue related to the bandgap combination of the absorbers. Specifically, the Ge bottom cell generates approximately 50% more current than the other two light-absorbing layers. Since the current in multijunction solar cells is constrained by the layer that produces the lowest photocurrent, according to Kirchhoff's current law, this excess current is effectively wasted as heat. To address this current mismatch problem, 4-junction PVs have been developed. These 4-junctions include an additional light-absorbing layer ($In_xGa_{1-x}N_yAs_{1-y}$) between InGaAs and Ge, effectively reducing the light reaching the Ge layer and its photocurrent. However, incorporating an InGaNAs layer in a lattice-matched configuration presents difficulties due to the growth methods employed, namely, MOVPE or MBE. To address these challenges, innovative fabrication techniques have emerged, allowing the use of materials with lattice mismatches. These techniques encompass the mechanical stacking method, metamorphic growth, and wafer bonding.[1][2]

THE FUTURE SPACE PV TECHNOLOGIES

Ongoing research focuses on integrating both III-V and Si into multi-junction PV devices. Hybrid III-V/Si multi-junction solar cells have shown excellent recent progress as it has been demonstrated that mechanically stacked or wafer-bonded III-V/Si solar cells can achieve comparable efficiencies under AM1.5G conditions as the conventional GaInP/GaAs/Ge triple-junction solar cells commonly used in space applications.[4]

Single-junction and multi-junction perovskite photovoltaics are also in the race as researchers have observed that perovskite solar cells when tested in space, experience less deterioration compared to reference devices tested on Earth and always retain above 90% of the efficiency even after radiation exposure in the space.[5][6]

CONCLUSION

In the current landscape of space missions, which has seen the privatization of these endeavors, there is a substantial need for more cost-effective photovoltaic (PV) technologies. Specifically, silicon-based solar cells are preferred for missions with lower power requirements and shorter durations due to their ability to strike a good balance between performance and production costs.

Furthermore, in the pursuit of minimizing both manufacturing and maintenance expenses while meeting the demands for lightweight and flexibility, researchers in academia and industry are primarily focusing on promising single-junction/multijunction thin-film perovskite photovoltaics that can reduce the costs associated with solar cells.

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