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Next Generation III-V Multi-Junction Solar Cells For Aerospace Applications

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The triple junction InGaP/GaAs/Ge solar cell has become the workhorse for powering spacecraft; from low-earth orbit sub-1W cubeSats through to large 15kW+ geostationary telecommunication satellites and most recently, deep space missions to the Jovian planets where extreme conditions such as low-light, temperature are compounded with high levels of radiation damage [1]. The cell architecture has gained this commanding position due to a combination of high efficiency and relative tolerance against radiation damage. Beginning of life efficiencies of 30% AM0 are offered by several commercial vendors, dropping only a few percentage points at end of life.

With the three component semiconductor junctions almost completely optimised, one of the few recent opportunities to further enhance the performance of the incumbent 3J technology has been to engineer the thermal properties of the solar cell were a PERC type rear contacting scheme was shown to reduce parasitic sub-gap absorption by 81% resulting that is anticipated to reduce the cell operating temperature by 9ºC [2]. Simultaneously, most commercial vendors are now offering quad-junction devices based around AlInGaP offering yet higher beginning of life efficiency [3].

An increasingly popular alternative triple-junction technology is the inverted metamorphic solar cell, that replaces the Ge junction with a more optimal relaxed InGaAs semiconductor. The device is grown in an inverted configuration ensuring that defects arising through the lattice relaxation of the InGaAs layer are confined in the low-band-gap, and hence low-voltage bottom junction. While this introduces complexity in the processing of the solar cell, it has the virtue of producing a very thin, light-weight, flexible solar cell that has achieved 1-sun efficiencies of 37.8% [4]. The high specific power [W/kg] of this photovoltaic technology has lent it to application in high-altitude pseudo satellites such as the Airbus Zephyr aircraft that flies at stratospheric altitudes, is powered entirely by PV and set a new flight endurance record in 2018 of 14 days [5] Since the solar cell is physically removed from the substrate, it also allows for the substrate to be re-used, offering a pathway to dramatic cost reduction from the present ~$100/Wp to, in extreme cases, costs below $1/Wp [6].

The inverted metamorphic solar cell has yet to be deployed at scale on spacecraft owing to a couple of reasons. Firstly a lightweight rigid array capable of leveraging the remarkable specific power of these PV cells has yet to be developed, but also they typically are less radiation tolerant than the conventional InGaP/GaAs/Ge devices. This has motivated work on schemes for achieving ultra-radiation hard solar cells.

In general, light-trapping is not employed in III-V solar cells since the junctions are composed of strongly absorbing, direct gap semiconductors. (Ge is current rich in the 3J configuration, owing to it's low band-gap so does not benefit from light trapping). However, two approaches have emerged where light-trapping can be used to achieve exceptional radiation resistance. Both rely on fabricating solar cells whose physical dimensions are much smaller than the minority carrier diffusion length at the beginning of life, thereby ensuring that complete carrier collection is maintained when the diffusion length is degraded at the end of life.

The concept of interstitial light trapping achieves wavelength selective light-trapping by placing a grating inside the multi-junction solar cell in conjunction with a Bragg reflector [7]. While technically challenging, this approach can be used to selectively enhance the absorption in an otherwise weak sub-cell within the multi-junction solar cell stack. In the example shown in Figure 1a, long-wavelength light can pass into the sub cell below unimpeded, while shorter wavelength light is scattered by the grating into oblique orders thereby making several passes through the thin, intermediate junction. A comparison in photocurrent is shown in Figure 1b, where two control devices with base thickness layers of 3500nm and 1750nm are shown, together with the interstitial light-trapping device marked as 'this-work' with a base thickness of 700nm. After exposure to 3E15cm^{-2} of 1MeV electron fluence, equivalent to the lifetime dose in geostationary orbit, the photocurrent from the interstitial light trapping device remains largely unchanged, while the photocurrent from the two control devices are significantly impaired.

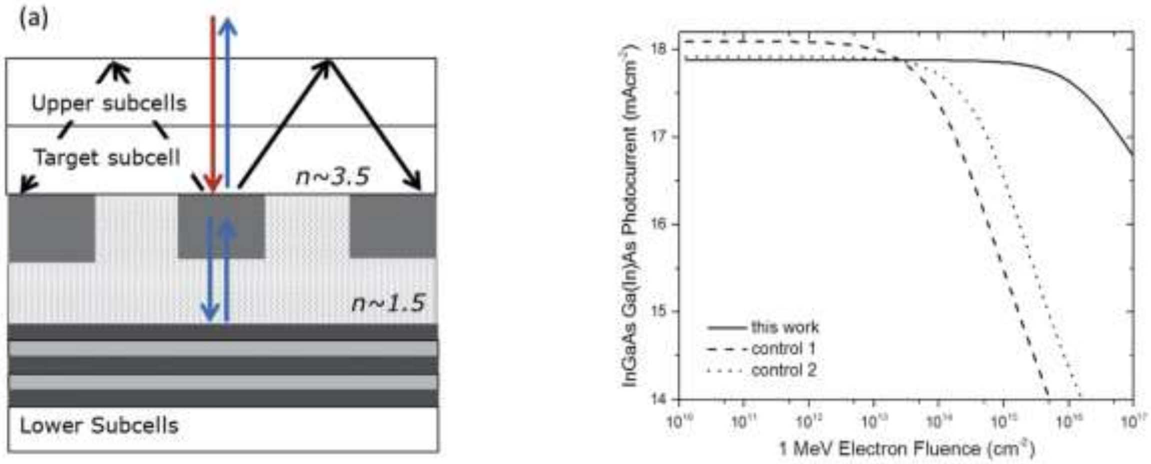

Figure 1. (a) The concept of interstitial light-trapping that selectively confines short wavelength light into the upper lying sub-cells of a multi-junction solar cell. (b) The middle cell short circuit current, for two control devices and the interstitial light-trapping device marked as 'this work' [7]

The ultimate in radiation tolerance is achieved using ultra-thin solar cells, with devices as thin as 80nm projected to show no degradation in short-circuit current when exposed to extremely high levels of irradiation (1E14.cm-2 3MeV proton fluence) [8]. To achieve this, broadband light-trapping is required on the nanometer scale. This appears to be feasible, with a three-fold increase in photocurrent projected from an 86nm GaAs solar cell using a hexagon metal-dielectric grating [9].

In summary, despite the maturity of the present InGaP/GaAs/Ge space solar cell, there remains a great deal of opportunity to develop solar cells for aerospace applications with ever higher efficiency, in lightweight and flexible formats and/or with very high levels of radiation tolerance.

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