Computational Optimization of Bragg Reflectors for InGaP/GaAs/Ge triple-junctions

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Multilayer reflectors incorporated into InGaP/GaAs/Ge triple-junctions can provide a targeted absorption boost for the middle cell, which can then be thinned to increase the cell's radiation tolerance for space applications. However, epitaxial growth limits material choice, which limits the reflected bandwidth of a typical quarter-wave reflector. Alternate thickness schemes such as linear thickness variation or double-section reflectors can enable further boosts in absorption, but thus far no systematic analysis of the designs available has been conducted. Here, epitaxial reflectors placed below the GaAs subcell are optically modelled and numerically optimized for GaAs thicknesses between 500 and 2000 nm and for reflector layer counts between 0 and 57. A simple quarter-wave stack performs as well as alternate schemes at lower layer counts. At higher layer counts, a design with two quarter-wave stacks combines high performance and relative simplicity. Thinner layers of GaAs benefit from this double-section reflector at lower total layer counts. A 1000 nm subcell with an optimized 57-layer reflector can achieve the same estimated current as a 2000 nm subcell with no reflector, suggesting that optimized reflector designs can increase radiation tolerance while maintaining high efficiency.

Context

Ionizing radiation creates defects in solar cells deployed in space; these defects act as recombination centres and traps for charge carriers in the device, which degrade carrier diffusion lengths and thus reduce power output. In thin cells with shorter paths to collection, reduced diffusion lengths do not prevent carrier collection, so the current remains stable up to higher doses of radiation [1]. However, thinner cells absorb less light. To simultaneously achieve high radiation tolerance and high efficiency, light trapping structures can be added. In standard InGaP/GaAs/Ge cells used in space, a distributed Bragg reflector (DBR) is often incorporated between the GaAs and Ge subcells during epitaxial growth (Figure 1a) to boost absorption in the GaAs, which degrades most acutely and limits the lifetime of the whole cell [2].

A DBR consists of alternating layers with contrasting refractive indices, where the thickness of each layer is typically a quarter of a target wavelength such that reflections from each interface interfere constructively at this wavelength. The reflected bandwidth of a quarter-wave DBR is determined by the refractive index contrast, but material choice is limited by the lattice constants of the stack. Figure 1b shows the bandwidth for an AlAs/$Al_{0.2}Ga_{0.8}As$ DBR centred at 830 nm, compared to the wavelength-dependent potential absorption enhancement. The quarter-wave DBR's bandwidth is most restrictive for thinner GaAs layers [3], which absorb less light on the first pass.

In order to broaden the bandwidth, more complex schemes can be implemented, such as a linearly "chirped" thickness variation [4]–[8] or a combination of two quarter-wave stacks [3], [9], [10]. Emelyanov et al. calculated that a double-section DBR, with 20 pairs of $Al_{0.1}Ga_{0.9}As$/AlAs and 20 pairs of $Al_{0.2}Ga_{0.8}As$/AlAs at different centre wavelengths, enabled a greater reduction in the optimal thickness of GaAs in a triple-junction cell than a typical single-section, 20 pair DBR [10]. Welser et al. simulated "composite chirped" reflectors with three linearly varied sections, totalling 12 and 24 pairs of $Al_{0.1}Ga_{0.9}As$ /AlAs. This design enabled higher short-circuit currents than conventional DBRs for GaAs thicknesses below 1000 nm in III-V quantum well solar cells [8]. These studies have shown the potential of unconventional DBRs in multijunction cells to enable thinner GaAs layers, but there has been no systematic analysis to guide their design.

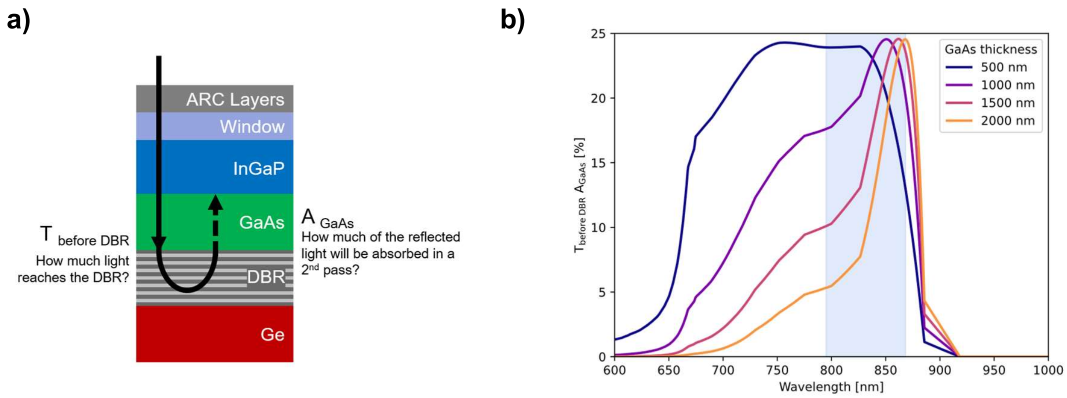

Figure 1. a) DBR in triple-junction cell. b) Profile of potential absorption enhancement ($T_{\text{before DBR}}\,A_{\text{GaAs}}$) for different GaAs thicknesses, with shaded area showing the limiting bandwidth of a quarter-wave DBR centred at 830 nm.

Method

This work investigates four different schemes, described in Table 1.

Table 1. Thickness schemes for DBRs.

Scheme	Description	Layer thickness, *d*	Parameters
1 CW (●)	Quarter-wave stack, with one centre wavelength (CW)	$d_{(1/2)} = \dfrac{\lambda_{CW}}{4n_{(1/2)}}$	λ_{CW}
2 CWs (▼)	Two quarter-wave stacks, with two different CWs. Variable number of layers allocated to each CW.	$d_{1(1/2)} = \lambda_{CW1}/4n_{(1/2)}$ $d_{2(1/2)} = \lambda_{CW2}/4n_{(1/2)}$	λ_{CW1}, λ_{CW2}, # layers to λ_{CW1}
Linear Chirp (■)	Design wavelength of each layer pair (index i) varies linearly from starting λ_{CW0}.	$d_{i(1/2)} = \dfrac{\lambda_{CW0}(1+Bi)}{4n_{(1/2)}}$	λ_{CW0}, B (chirp parameter)
Unrestricted (★)	Layer thicknesses can vary arbitrarily (10-150 nm)	N/A	All layer thicknesses

$Al_xGa_{1-x}As$ compounds are selected for the DBR for their compatible lattice constants. AlAs provides the lowest refractive index available, and $Al_{0.2}Ga_{0.8}As$ provides a compromise between refractive index contrast and absorption.

For optical modelling and optimization, a simplified structure replacing junctions with bulk layers is defined, with thicknesses listed in Table 2. The structures are defined using the Python library Solcore [11] and its material database, and their optical behaviour is modelled in Solcore using the transfer matrix method (TMM). The fraction of normally incident power absorbed by the GaAs layer at each wavelength is integrated with the solar photon flux at AM0 to calculate the limiting photo-generated current (J_{sc}) for each design. Numerical optimizations are run at fixed GaAs thicknesses and fixed DBR layer counts between 0 and 57. The parameters listed in Table 1 are varied to minimize $-J_{sc}$ (i.e. maximize J_{sc}), using differential evolution with the Python library pygmo [12].

Table 2. Details of structures modelled.

Role	Material	Thickness
ARC layers	Al_2O_3 TiO_2	90 nm 52 nm
Window	$Al_{0.52}In_{0.48}P$	25 nm
Top cell	$In_{0.49}Ga_{0.51}P$	500 nm
Middle cell	GaAs	500, 1000, 1500, 2000 nm
DBR	$AlAs/Al_{0.2}Ga_{0.8}As$	variable
Bottom cell	Ge	1000 µm

Results

The maximum current achievable for a given scheme and layer count is plotted in Figure 2 for the four GaAs thicknesses considered. All schemes perform comparably until the 1 CW scheme becomes limited by its bandwidth and yields negligible increases to absorption with additional layers. Beyond this split, 2 CWs designs slightly outperform linear chirp and unrestricted designs slightly outperform 2 CWs. For 500 and 1000 nm GaAs layers, the 2 CWs scheme also becomes bandwidth limited.

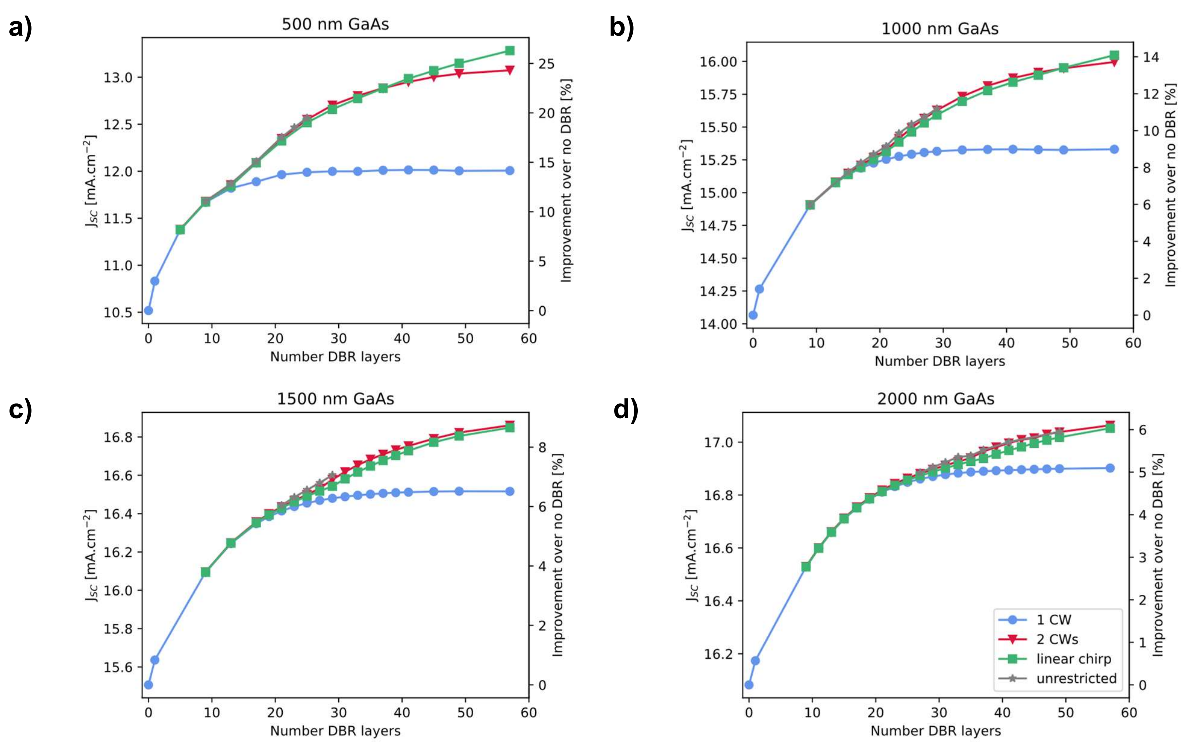

Figure 2. Optimized J_{sc} vs layer count for each scheme, for a) 500, b) 1000, c) 1500, and d) 2000 nm GaAs thicknesses.

The optimal scheme depends on the layer count and GaAs thickness. At lower layer counts, 1 CW DBRs are preferred for simplicity. Thinner cells benefit most from DBRs but are limited by the bandwidth of the 1 CW scheme from lower layer counts. The unrestricted optimization provides *at most* a 0.26% relative improvement over 2 CWs, corresponding to 0.04 $mA.cm^{-2}$. The unrestricted optimization places an upper limit on the increases obtainable through unexplored schemes.

Therefore, although 2 CWs is not the absolute optimum, its performance is equivalent with a relatively simple design.

The optimized parameter values for each scheme vary with GaAs thickness and number of DBR layers. Additional effects such as absorption in the DBR and the wavelength-dependent phase shift on reflection have been identified, and their impact on optimal layer order has been mapped.

A 1500 nm GaAs layer with a 9-layer DBR and a 1000 nm GaAs layer with a 57-layer DBR yield the same current as a 2000 nm subcell with no DBR. An optimized structure can thus halve the GaAs thickness while maintaining the same pre-radiation current. Particularly for thinner subcells, the use of a 2 CWs scheme is recommended to unlock absorption enhancements inaccessible to typical DBRs.

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