# Chapter 55
# Analytical Models of Bulk and Quantum Well Solar Cells and Relevance of the Radiative Limit

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## ABSTRACT

*The analytical modelling of bulk and quantum well solar cells is reviewed. The analytical approach allows explicit estimates of dominant generation and recombination mechanisms at work in charge neutral and space charge layers of the cells. Consistency of the analysis of cell characteristics in the light and in the dark leaves a single free parameter, which is the mean Shockley-Read-Hall lifetime. Bulk PIN cells are shown to be inherently dominated by non-radiative recombination as a result of the doping related non-radiative fraction of the Shockley injection currents. Quantum well PIN solar cells on the other hand are shown to operate in the radiative limit as a result of the dominance of radiative recombination in the space charge region. These features are exploited using light trapping techniques leading to photon recycling and reduced radiative recombination. The conclusion is that the mirror backed quantum well solar cell device features open circuit voltages determined mainly by the higher bandgap neutral layers, with an absorption threshold determined by the lower gap quantum well superlattice.*

## INTRODUCTION

Despite great advances in physical understanding, in materials, and in fabrication, and despite reaching efficiencies over 40%, just two routes to higher efficiencies have been comprehensively studied. The first is the multi-junction cell concept, which reduces thermalisation losses. The second is the use of light concentration, reducing the solid angle for light emission towards the minimum, which is the angle for light acceptance (de Vos, 1992). The current interest in novel phenomena, often involving nanostructures, is part of the effort to go beyond these early ideas.

This chapter investigates generation and loss mechanisms in bulk and quantum well solar cells, with emphasis on developing physical understanding via analytical models, rather than more accurate

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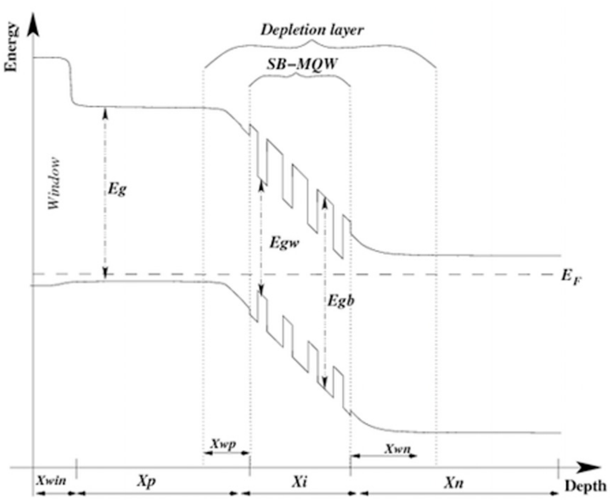
but less revealing numerical methods. The designs studied are bulk PIN cells contrasted with Quantum Well Solar Cells (QWSCs), complementing other nanostructured designs reviewed in other chapters.

The quantum well solar cell (QWSC, Figure 1) is a *p-i-n* or *n-i-p* solar cell design with Quantum Wells (QWs) in the undoped intrinsic *i* region (Barnham & Duggan, 1990). Carrier escape studies show efficient field assisted thermal escape of the order of picoseconds, for carrier lifetimes of several nanoseconds (Nelson, Paxman, Barnham, Roberts, & Button, 1993). Early Quantum Efficiency (QE) modelling (Paxman, et al., 1993) further shows that escape efficiency is essentially 100%. More recent theoretical work by Tsai and Tsai (2009) confirms this while showing that escape times must be at least two orders of magnitude shorter than recombination lifetimes for a net efficiency again to be achievable.

Consequently, however, it is clear that this efficient collection requires that the field be maintained across the wells. The nominally undoped wells and barriers however inevitably contain a net background doping level, corresponding to a fixed charge density, which increasingly degrades the built in field, the wider the Multiple Quantum Well (MQW) superlattice is grown. This brings us to the first design issue with these cells, which is the practical upper limit on total intrinsic region thickness *Xi* and corresponding limit on absorbing MQW thickness that may be fabricated. This materials quality dependent limit may extend well over 1μm, and even in direct gap quantum wells makes this system well suited to light trapping techniques, as we will see in subsequent sections.

More recent analytical models by Rimada, Hernàndez, Connolly and Barnham (2007) have followed a similar analytical methodology confirming early results that an MQW can enhance efficiency in non-ideal, high bandgap cells, but do not demonstrate an advantage for ideal material. The MQW bandgap together with near unit collection efficiency leads to a net increase in short circuit current (ISC). This increase in Isc however is accompanied by an increase in recombination in the low gap well regions, as discussed in some detail by Anderson (1995) for example.

*Figure 1. The strain balanced quantum well solar cell (SB-QWSC) structure. Alternating strain balanced wells and barriers of gaps Egw, Egb make up the intrinsic region of total width Xi, which is sandwiched between p and n doped layers of width Xp, Xn, and bandgap Eg, with an optional higher bandgap window layer. Widths are not to scale, and typical QWSCs contain some tens of QW periods.*



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