Growth and characterization of high efficiency III−V multijunction solar cells for terrestrial and space applications

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Introduction

Heretofore, III−V solar cells have always been considered too expensive for terrestrial photovoltaics because of the expense of the materials and processes involved in their production. Recently it has been shown that the cost (<$10/cm^2) and efficiency (~34% at 500X) of GaInP/GaAs devices make them attractive for concentrator systems. In the following, we review the recent progress in III−V multi−junction solar cells and discuss some of the research aimed at increasing the efficiency from the current 34% to over 40%.

Background

The development of III−V multi−junction concentrator cells began in the early 1980's. There were basically two approaches: (1) the combination of a III−V top cell with a band gap of about 1.7 eV (such as GaAsP) grown monolithically on a Si bottom cell and (2) the combination of a 1.9 eV AlGaAs top cell grown monolithically on a 1.4 eV GaAs bottom cell. The former suffered from problems associated with the lattice mismatch and thermal expansion mismatch between Si and most III−V semiconductors and the latter (although it had achieved very respectable efficiencies for its time) suffered mainly from problems associated with the oxygen sensitivity of AlGaAs−based semiconductors [1]. In 1984, researchers at the National Renewable Energy Laboratory in the United States, invented the oxygen−tolerant, lattice−matched GaInP/GaAs tandem cell which today is the industry standard for very high efficiency solar cells.[2]

GaInP/GaAs/Ge Solar Cells

A schematic of the GaInP/GaAs solar cell is shown in Fig. 1. The original devices were grown on GaAs substrates. For reduced cost and weight and increased mechanical strength they are now often grown on Ge substrates. The Ge substrate is closely lattice−matched to GaAs and can also be "activated" to provide a voltage boost to the output of the device.

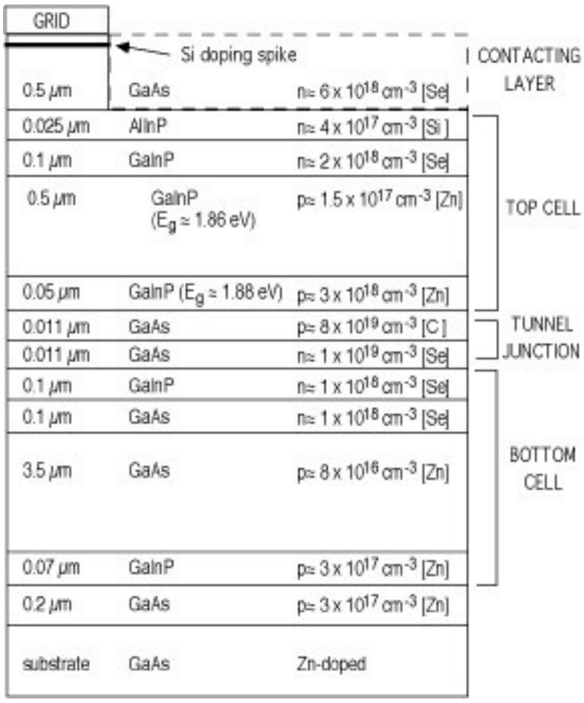

Figure 1 Solar cell structure for the AM0 standard spectrum. For AM1.5G, the base layer of the top cell is 0.6µm thick. For a concentrator cell, the top−cell emitter layer is 0.2µm thick and the base layer is from 0.6µm to 1.2µm thick depending on the spectrum.

Space Cells

The GaInP/GaAs/Ge solar cell is manufactured in large volume by MOVPE by several US companies for use in powering communication satellites in space. The main advantage of this device compared to a Si solar cell is higher efficiency both at the beginning of the mission (called beginning−of−life or BOL) and near its end−of−life (or EOL). The EOL efficiency is usually much lower than the BOL efficiency due to the degrading effects of the radiation that is commonly encountered in the space environment. The BOL efficiency of a GaInP/GaAs/Ge space cell is approaching 30% with an EOL efficiency of 22.5%. On the other hand, the best silicon solar cells are 18−19% at BOL and close to 12% at EOL. This advantage allows the satellite manufacture to design and build more power−hungry systems for a given photovoltaic array area or weight despite the extra cost of the GaInP/GaAs/Ge cell compared to the Si space cell.

Concentrator Cells

The GaInP/GaAs/Ge solar cell has also achieved record success in the area of terrestrial high efficiency concentrator solar cells. The efficiency of devices grown by Spectrolab Inc. in the US, and processed and measured at the National Renewable Energy Laboratory, has exceeded 34% for concentration levels of 100X to 500X. As a result, these solar cells are now being evaluated for use in high flux concentrator systems such as that developed by Amonix, Inc. for Si concentrator solar cells.

Future Multi−junction Solar Cells

There are a large number of options to study in the field of multi−junction solar cells and it is beyond the scope of this paper to discuss all of them. As such, we will address the following topics:

- Monolithic, lattice−matched, 3− and 4−junction devices on Ge .
- Monolithic, lattice−matched, multi−junction cells on Si.

Multi−junction solar cells on Ge

The GaInP/GaAs tandem cell is a natural starting point for building more complex multi−junction solar cells. To a limited extent this has already been done with the addition of a Ge booster cell. Over the last few years a number of additional options have been proposed. These are summarized in Fig. 2. In the first option, the GaAs cell in a three junction GaInP/GaAs/Ge triple is replaced with a cell having the same lattice constant but a band gap of 1.25 eV (e.g. GaInNAs). This better utilizes the photons with energies greater than 1.25eV, yielding a device with a lower Voc but even greater Jsc. (This is also the rationale behind lattice−mismatched GaInP/GaInAs/Ge solar cells proposed by numerous groups.) The second option is to insert a solar cell below the GaAs cell. Ideally, this solar cell should be lattice−matched to GaAs and have a band gap close to 1.0 eV.

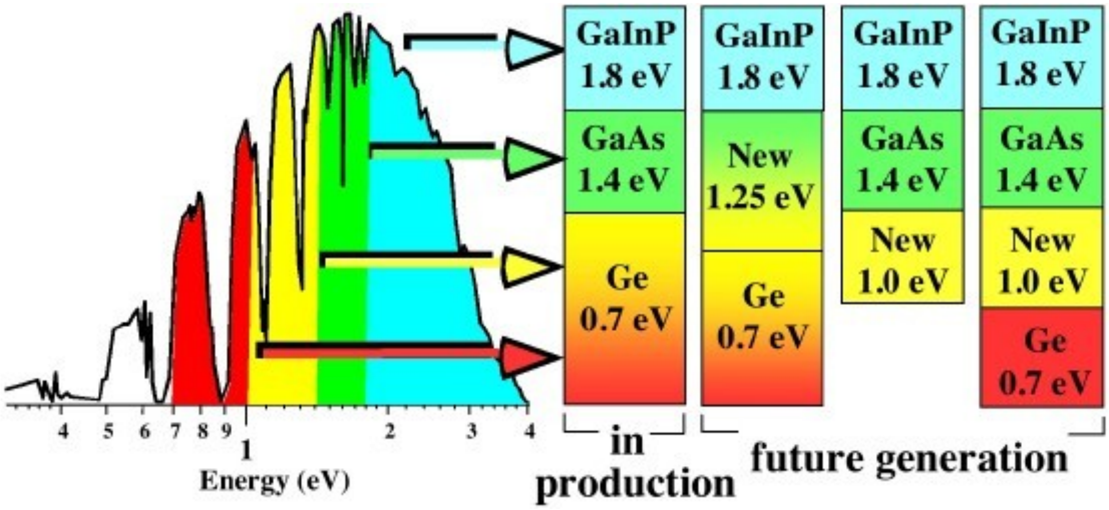

Figure 2 Options for multi−junction solar cells based on the GaInP/GaAs/Ge triple junction solar cell. The predicted practical AM1.5G efficiencies at 500X for each cell structure, proceeding from left to right, are 36%, 38%, 37%, and 40%.

The most promising 1−eV semiconductor material is the dilute nitride alloy GaInAsN. It was shown in 1996 by Kondow and coworkers [3] that because of an unexpectedly large negative bowing parameter for N in GaAs, $Ga_{1-x}In_xAs_{1-y}N_y$ could be grown lattice−matched to GaAs with a band gap as low as 0.9 eV. At first sight this looked very encouraging and, indeed, we were able to grow specular, epitaxial, GaAs−lattice−matched layers with bandgaps of 1.0 eV [4] and a 4−junction solar cell seemed well in hand. However, the first devices were less than perfect [4,5]. Using a conventional base doping of around 10^{17} cm^{-3}, the short−circuit current and internal quantum efficiency (IQE) for this material were very low. By counter doping the base and increasing the depletion width, the Jsc and the IQE could be increased substantially, albeit with a concomitant decrease of the Voc and fill factor. At first, it was thought that this was simply an extrinsic problem associated with source purity or growth conditions. But after a considerable effort, it was determined that this is not the case. It now appears that minority carrier lifetime and mobility in GaInAsN is caused by a deep state associated with N. The nature of this state has been theoretically modelled [6] and could be the so−called N−N split interstitial. This state is ostensibly more stable thermodynamically than a N−As split interstitial or an As_{Ga}−N_{As} defect complex and should be electrically active with a deep state near the middle of the gap in $GaN_x As_{1-x}$. Confirmation of these predictions is in progress.

Silicon−based lattice matched multi−function solar cells

The ideal band gap combination for a dual junction solar cell is 1.7 eV for the top cell and 1.1 eV for the bottom cell. Silicon is an obvious candidate for the bottom cell, but it was not until recently that there were viable materials for a lattice−matched 1.7 eV top cell. One such material is GaAsNP [7]. The III−V semiconductor GaP is closely lattice−matched to Si but has a band gap that is indirect and much larger than the ideal band gap. The addition of As or N will drive the band gap of the ternary ($GaAs_xP_{1-x}$ or GaN_yP_{1-y}) lower. However, the lattice constant of $GaAs_xP_{1-x}$ increases with x while that of $GaP_{1-y}N_y$ decreases with y. Hence there exists a combination of x and y where the band gap of $GaAs_xN_yP_{1-x-y}$ equals 1.7 eV and the lattice constant is equal to that of Si. To date, solar cells of GaAsNP, grown by MOCVD on GaP substrates, are of relatively poor quality [7]. This appears to be at least partly caused by unintentional C and H doping and is mitigated to some extent by the use of TEGa (as opposed to TMGa) and lower growth rates, as shown in Fig. 3. There is some indication that this material is less affected by N−related defects.

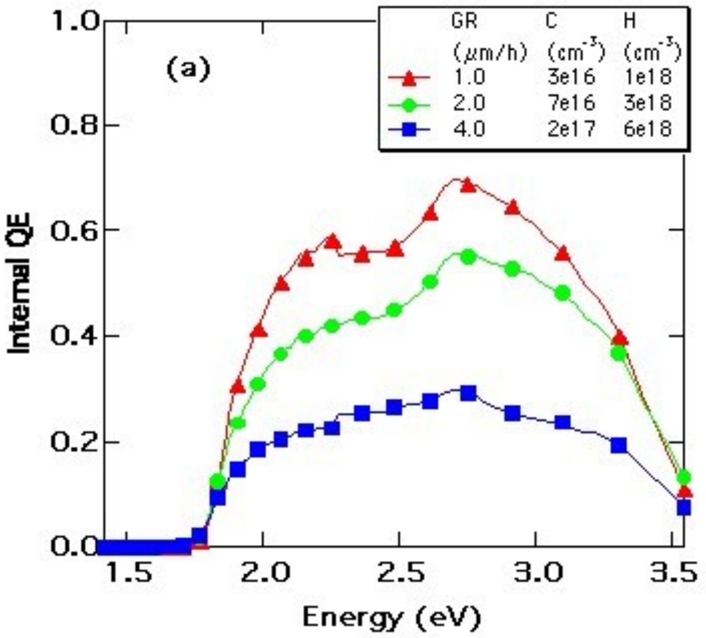

Figure 3. Internal quantum efficiency of three GaAsNP cells grown at different growth rates. The growth temperature and dimethylhydrazine/phosphine ratio were fixed at 650C and 2.1, respectively. The C and H concentrations were measured with SIMS. (from Geisz, Reedy and Keyes, submitted for publication)

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